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THE JOURNAL OF GEOLOGY

November 1950

LOESS FORMATIONS OF THE MISSISSIPPI VALLEY[1]

MORRIS M. LEIGHTON AND H. B. WILLMAN
Illinois State Geological Survey

ABSTRACT

The loess deposits of the Mississippi Valley area are widespread and have been extensively studied. In the upper valley they have definite stratigraphic relationships to the drift sheets. From these relationships they are known to have a definite stratigraphic sequence, and their ages have been, in the main, closely determined.

They show an eolian genetic relationship to source areas by their thickness, texture, structure, topographic position, and percentage composition of carbonates. Their eolian origin is also indicated by their faunal and, in places, floral assemblages. Some of the loess deposits also reflect the climatic conditions under which they accumulated and the rate of deposition with respect to rate of solution of carbonates. Where they carry plant fossils, the nature of the vegetation which was growing on the surface at the time of deposition is recorded.

The stratigraphic sequence that prevails in the upper valley can be unmistakably traced into the lower valley to beyond Natchez, Mississippi, in all its principal attributes. The authors find no substantial evidence to support the "loessification" theory of R. J. Russell and H. N. Fisk or for the Pleistocene correlations and events which they postulate, based on their hypothetical mode of origin of the loess.

INTRODUCTION

One of the most important and best-known occurrences of loess in the world is in the Mississippi River Basin. Here, in an area of more than 200,000 square miles, about half of which is glaciated, are exhibited nearly all, if not all, the phenomena associated with such deposits. Here can be studied their stratigraphic succession, genetic relationships to source areas, distribution, modes of occurrence, topographic expression, physical and chemical composition, structure and properties, faunal and floral assemblages, weathering phenomena in response to various conditions, mode of origin, and other matters which concern this most interesting Pleistocene deposit.

That the several loesses in the upper Mississippi Valley[2] are wind-blown is universally held by those geologists who have extensively studied them. Some of these, including the authors (1949, p. 5), who have extended their observations southward, regard the loess deposits of the lower Mississippi Valley as also of eolian origin and continuous with those of the upper valley. Some geologists, however, who have given their attention chiefly to the loess of the lower Mississippi Valley, as, for example, R. J.

[1] Manuscript received February 28, 1950.

[2] Upper Mississippi Valley, as here referred to, consists of that portion of the valley north of Commerce, Missouri, above the junction of the Ohio Valley, and exclusive of it and the Missouri Valley. The lower Mississippi Valley, therefore, consists of that portion of the valley which crosses the Coastal Plain. Reference may be made to base maps of the states for place names in this paper.

Russell (1944*a*)[3] and H. N. Fisk (1944), do not accept the eolian theory of origin.

Russell and Fisk regard the loess as having been derived from backswamp alluvial deposits by a process called "loessification," which, as conceived and defined by Russell (1944*a*, p. 30), begins with eluviation of the clay content of backswamp deposits, accompanied and followed by leaching of lime carbonate and its deposition at lower levels in the silt from which the clay has been eluviated, and, finally, entombment by creep and wash of the shells of snails which lived in the vegetation of lime-charged silts on erosional slopes.

Russell and Fisk both believed that they were dealing with floodplain silts overlying sands and gravels, although there is no evidence of such an origin. It would have been revealing had they investigated the loess farther north, where it rests on Paleozoic rocks rather than on sand and gravel, and still farther north, where it rests on glacial till. The result is that their geological interpretations of the loess and other phenomena of the lower valley stand in wide variance from those held by workers in the upper valley.

Russell's studies (1944*a*, pp. 2, 33, 34) of loess in the Rhine Valley led him to believe that it also was a colluvial deposit. However, recent studies in the Netherlands (Van Doormaal, 1945; Vink, 1949) support the eolian origin of Rhine Valley loess.

The authors of the present paper extended their studies in 1948 into the lower Mississippi Valley as far as Natchez, Mississippi. They initiated a two weeks' field conference, held in June, 1949, in co-operation with the state geologists of the states involved, which was concerned with the area from the latitude of Iowa City, Iowa, south to Natchez, Mississippi. This provided opportunity for nearly twenty Pleistocene specialists to observe the phenomena of the loess throughout a traverse of over 2,000 miles (fig. 1). About twenty others joined the party for shorter distances.

This paper will summarize the stratigraphic sequence, geographic occurrence, and character of the loess formations from eastern Iowa to southern Mississippi and will analyze the question of origin in the light of these phenomena.

Loess Deposits in the Upper Mississippi Valley

STRATIGRAPHY

The loess deposits in the upper Mississippi Valley occur in stratigraphic sequence. They range in age from pro-Kansan? (that is, in advance of the oncoming Kansan ice sheet) to Mankato, as shown in figure 2.

PRO-KANSAN? LOESS

Buried beneath two drift sheets, the pro-Kansan? loess is not well known; but Savage and Udden (1921) record a well section at Rock Island, Illinois, at the base of the bluff near Seventh Avenue and Thirty-fifth Street, which revealed fossiliferous loess directly beneath Kansan drift, apparently without evidence of a weathering interval. The possibility that the advancing Kansan ice may have cut away the weathered zone, if it once existed, is to be considered. The presumption is that it was blown from a valley train of the advancing Kansan ice.

No definite record of loess deposition immediately following the retreat of the Kansan—or of the older Nebraskan, for that matter—is known. However, it is suggested that the profiles of weathering on those drifts, especially where abnormally thick, be scrutinized for the occur-

[3] For reviews of Russell's paper (1944*a*) see Holmes (1944) and Thwaites (1944) and the reply to Holmes by Russell (1944*b*).

rence of gumboloess on gumbotil. Advanced weathering, so characteristic of those two oldest drifts, would make thin loess difficult to distinguish from the underlying gumbotil.

PRO-ILLINOIAN LOESS: LOVELAND

Immediately below the Illinoian drift, an unweathered fossiliferous loess is exposed at several localities widely distributed along the middle and lower Illinois Valley, from La Salle County south to Scott and Greene counties, and in western Illinois, including the Rock Island area. Nowhere has it been found to show a weathered zone. For this reason it is believed to have been blown from

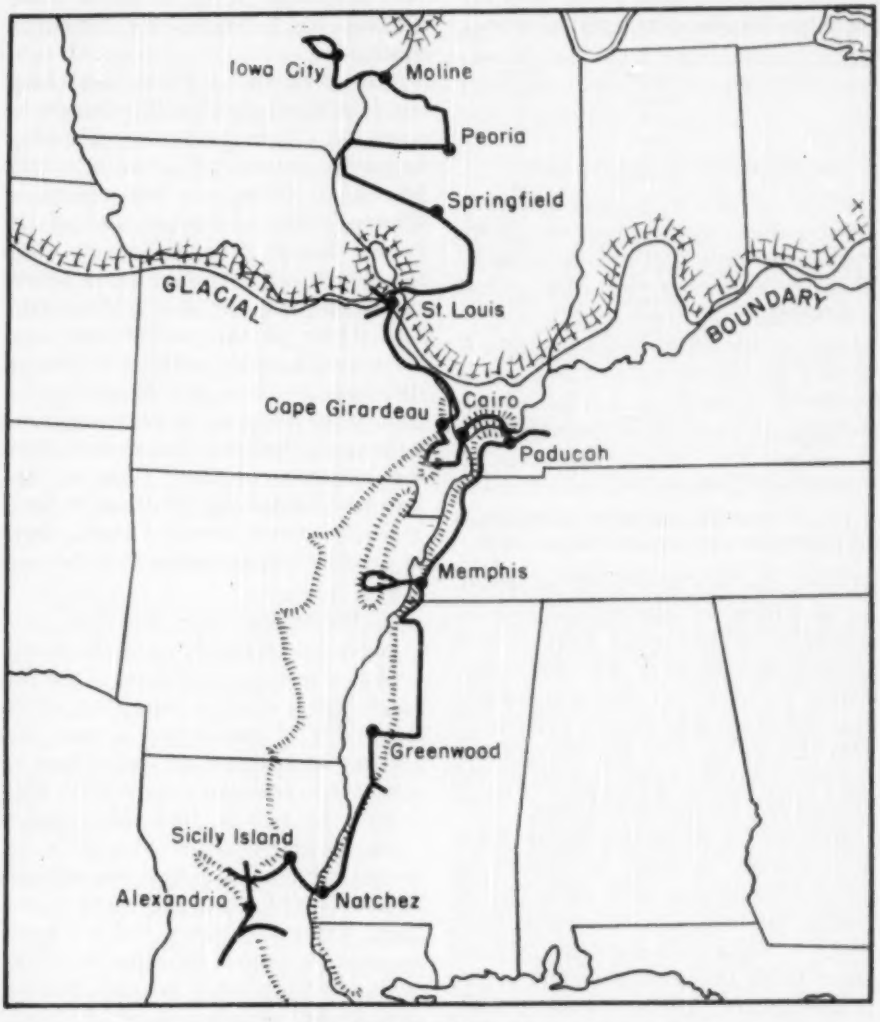


FIG. 1.—Route of Mississippi Valley field conference, June 22–25, 1949

the valley train of the approaching Illinoian glacier and therefore to be pro-Illinoian in age. It seems to have the same age relationship to the Illinoian drift as the fossiliferous Iowan loess has to the Tazewell drift of the Wisconsin stage.

In the Schuline exposure, 7 miles southwest of Sparta, Illinois, described by MacClintock (1929), the loess beneath the Illinoian drift is noncalcareous.

Stage	Sub-stage	Materials
WISCONSIN	Mankato	Loess*
		Till
	Cary	Loess*
		Till
	Tazewell	Loess*
		Till
	Iowan	Loess*
		Till
	Farmdale (Pro-Wis.)	Loess
SANGAMON		Gumbotil
ILLINOIAN	Buffalo Hart Jacksonville Payson	Till
	Loveland (Pro-Ill.)	Loess
YARMOUTH		Gumbotil
KANSAN		Till
	Pro-Kansan?	Loess
AFTONIAN		Gumbotil
NEBRASKAN		Till

*Peorian where not differentiated.

FIG. 2.—Composite stratigraphic column of loess and drift formations in upper Mississippi Valley.

At first, this was interpreted as recording an interval of leaching, but now the possibility is recognized that at this locality, remote from the Mississippi Valley, the loess may have accumulated at a rate slower than the rate of leaching. This view harmonizes with the fact that the loess rests on Kansan gumbotil, the product of Yarmouth weathering.

However, in the quarry section south of St. Charles, Missouri, just beyond the limits of the Illinoian drift sheet, Guy D. Smith[4] has recognized Loveland loess, which he has traced along the Missouri River to its area of common occurrence in northwestern Missouri, western Iowa, eastern Kansas, and eastern Nebraska. At St. Charles the Loveland loess is much weathered, and this weathered zone is overlain by Farmdale loess and Peorian loess in normal succession. The present authors correlate the Loveland loess here with the pro-Illinoian loess found a short distance to the north along the Illinois River. The weathering of the Loveland loess is credited to the remainder of the Illinoian epoch and to the Sangamon epoch.

The geologists of Illinois and Iowa recognize that before the Illinoian glacial epoch, as well as during the succeeding Sangamon interval, the course of the Mississippi River was from south of Clinton, Iowa, to the big bend of the present Illinois River and thence down the Illinois River, except for a detour east of Peoria, to the present Mississippi. The source of the pro-Illinoian loess along the Illinois River Valley is thought, therefore, to be a pro-Illinoian valley train along the ancestral Mississippi and its major tributaries that drained from the advancing glacier. Likewise, the Loveland loess along the Missouri River Valley is believed to record a valley train of pro-Illinoian age along that drainage line.

PRO-WISCONSIN LOESS: FARMDALE

A silt deposit which lies on the weathered zone and erosional slopes of the Illinoian drift and which has a very youthful profile of weathering beneath the Peorian loess was recognized as loess by Leighton in 1920 and described in a publication by him in 1926. He called it "Late Sangamon loess" but later renamed it "Farmdale" from the exposure in the Farm Creek section near Farmdale, Tazewell County, Illinois (communication quoted by Wascher, Humbert, and Cady, 1948, p. 390). In time, field studies by him and others showed that it, like the overlying Peorian loess,

[4] Personal communication.

has definite valley relationships to the Illinois River Valley (ancestral Mississippi), the present Mississippi Valley below the mouth of the Illinois River, and the Wabash and lower Ohio valleys. Such a relationship strongly suggests a valley-train source. This, in turn, implies an extension of an ice sheet during the Farmdale substage into the drainage basin of the ancestral Mississippi prior to the Iowan substage but not yet recognized in the series of drift sheets because it fell short of subsequent ice lobes. Antevs' modification of the Spitaler-Milankovich-Köppen chronology designates such a cold period at 100,000–90,000 years ago, and he suggests (1938) that at this time there was development of the Keewatin center.

The present authors, therefore, are inclined to the belief that the Farmdale loess is pro-Wisconsin. This is supported by the fact that the profile of weathering on the Farmdale loess and beneath the Iowan loess is very youthful and records only a brief interval when compared to the Sangamon profile of weathering beneath it on the Illinoian drift (Leighton, 1926, p. 170).

PEORIAN LOESS

The Peorian loess is definitely of Wisconsin age. It is a multiple loess in western and southern Illinois and undoubtedly elsewhere, being composed primarily of Iowan and Tazewell loesses, with probably some Cary and possibly some Mankato loess. In Nebraska (Schultz and Stout, 1945) and Kansas (Frye, Swineford, and Leonard, 1948) a loess, called "Bignell," is assigned by the authors cited to the Mankato substage.

In Illinois, west and south of the Shelbyville terminal moraine (outermost Tazewell), the Iowan loess constitutes the lower part of the Peorian loess, the upper part being Tazewell and possibly some Cary loess. There is no clear separation of the Iowan and Tazewell loesses except at the border of the Wisconsin drift, where the Iowan loess lies under, and the Tazewell loess lies upon, the Shelbyville drift, in both cases without any evidence of a weathering interval (Leighton, 1931).

The Peorian loess outside the Wisconsin drift border is thicker than the Tazewell loess on the Wisconsin drift. Smith's map of the thickness of the loess in Illinois shows conspicuous offsets in the thickness patterns at the Wisconsin drift border (fig. 4).

GEOGRAPHIC OCCURRENCE

That there are several loesses in stratigraphic succession—and therefore of different ages—and that they occur interbedded with drift sheets and upon the surface of drift sheets have been shown. We shall now deal with their geographic occurrence. Certain areas will also be selected for a more detailed description of the loesses as formations, of their thickness and textural relationships to source areas, their mode of origin, their weathering, and other phenomena.

Figure 3 is a generalized map showing the geographic distribution of the loess deposits along the Mississippi River Valley and portions of its major tributaries.

The loess-free lobate tract in northern Iowa is due to the invasion of the Mankato lobe subsequent to the deposition of the pre-Mankato loess in that area. The border loess of the Iowan drift lobe is found to pass under the Mankato drift.

The Iowan drift area in northeastern Iowa, characterized by scanty loess, was a source area from which the loess surrounding it was derived. The nearly loess-free areas of northeastern Illinois and of adjacent parts of Wisconsin and Indiana are due partly to the distance from source areas of silt, the valley trains of that area being largely coarse sand and

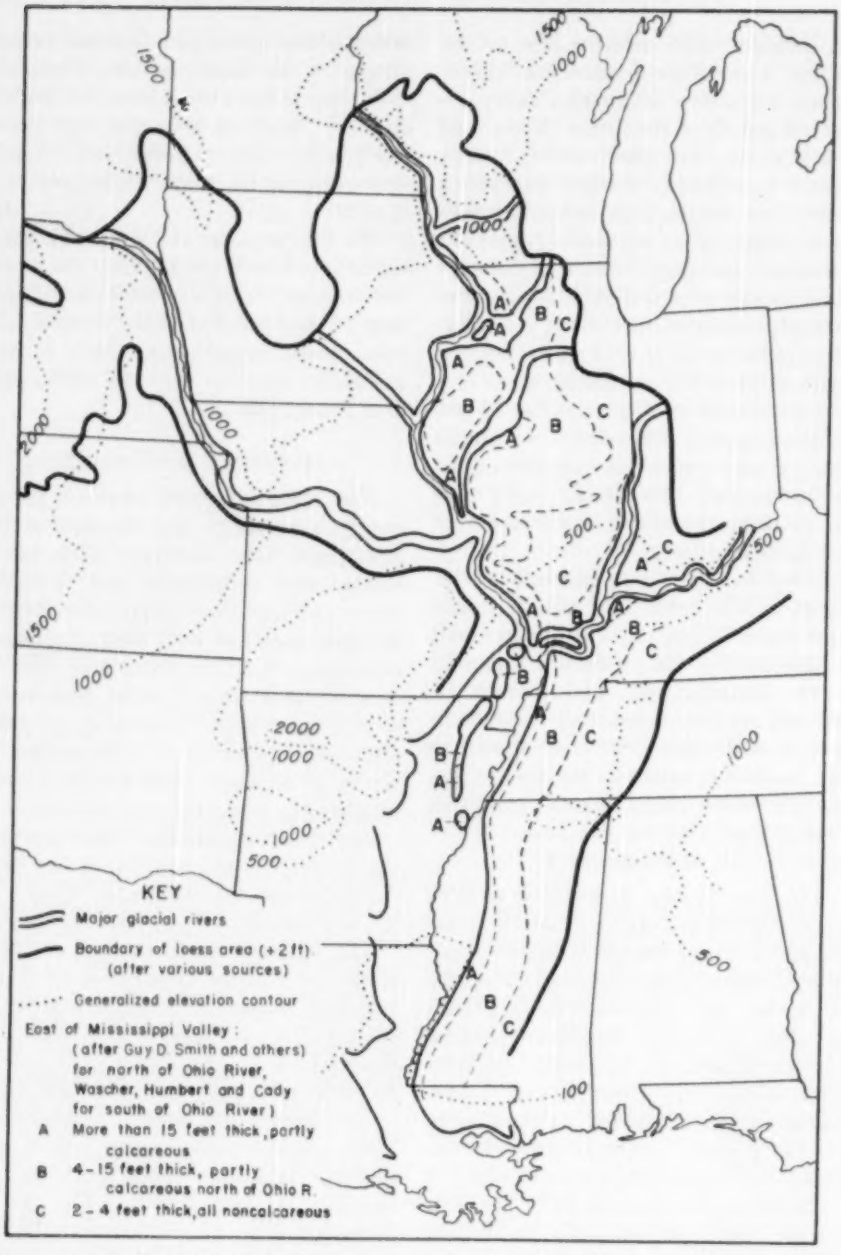

KEY
Major glacial rivers
Boundary of loess area (+2 ft) (after various sources)
Generalized elevation contour
East of Mississippi Valley: (after Guy D. Smith and others) for north of Ohio River, Wascher, Humbert and Cady for south of Ohio River)
A More than 15 feet thick, partly calcareous
B 4–15 feet thick, partly calcareous north of Ohio R.
C 2–4 feet thick, all noncalcareous

FIG. 3.—Generalized distribution of loess deposits in Mississippi Valley (loess more than 2 feet thick). In Illinois the thickness generally includes the Peorian and Farmdale loesses. In the lower Mississippi Valley the thickness of A and B is Peorian, the thickness of C is undifferentiated loess.

gravel. With the exception of the Iowan drift area, the drift sheets in general did not yield silt to the winds. The tract of scanty or no loess along the western side of the lower alluvial valley of the Mississippi is due primarily to the direction of the winds in reference to available silt.

LOESS DEPOSITS OF EASTERN IOWA

The outstanding feature of the loess deposits of eastern Iowa is the marginal relationship of the loess to the Iowan drift sheet (Calvin, 1911; Alden and Leighton, 1917; Kay and Graham, 1943, fig. 69). This relationship is a most remarkable phenomenon of glacial winds during the early stages of the retreat of the Iowan glacier.

As described in various papers by Calvin, Alden and Leighton, Kay, and others (Kay, 1944), the loess deposits at the border of the Iowan drift rise prominently above the Iowan drift plain in a manner simulating morainal deposits, which they are not. From a thickness commonly of 2 or 3 feet on the plain, the loess attains a thickness of 50 or more feet at the border, where it is a sandy silt to silt with dunelike forms; but away from the border, on the Kansan drift, it becomes thinner and finer. Save for a leached zone of approximately 5 feet, the loess at or near the border is calcareous and in many places fossiliferous, the fossils being pulmonate gastropods. The gastropod fauna changes from deep-woodland forms near the base to those of forest border or prairie higher in the section (Kay and Graham, 1943, p. 192).

Plant roots occur in the loess at Iowa City (Kay and Graham, 1943, pp. 168, 169) and logs and woody material in the loess (Iowan) beneath the Mankato till in the "Mitchellville cut," about 6 miles north of Mitchellville, Polk County, Iowa (Kay and Graham, 1943, pp. 169–171). In Illinois a floral assemblage from loess of Iowan age (formerly referred to as "Early Peorian"), beneath Tazewell till, has been collected by Leighton and Voss and described by Voss (1933; see also Leighton, 1931, pp. 48, 49). Other occurrences are known, but all are below a capping of later till, which has preserved the loess from being altered by weathering. It thus seems clear that the character of the loess as originally laid down and that of the oxidized loess as commonly observed are in striking contrast (Leighton, 1931, p. 49).

That the loess around the Iowan border is of eolian origin is shown by its uniform gradation from sandy loess at the border to a finer-grained texture farther away; by its fossil content; and by its topographic position as a general mantle on slopes and divides alike and on the highest hills. That it was blown by glacial winds from the Iowan drift plain is evident from its border relationship, its similarity to the drift chemically and mineralogically, the similar stage of weathering profiles, a pebble concentrate, including ventifacts, on the surface of the Iowan drift beneath a scanty loesslike silt, and from the fact that where the loess is thick enough to be calcareous in its basal portion, the underlying Iowan drift is also calcareous.

The Iowan drift and its counterpart, the Iowan loess, are much younger than the Kansan drift, as is shown by the occurrences of Kansan gumbotil underlying both.

This border relationship of loess to the Iowan drift sheet is unique. No such relationship to other drift sheets exists in the Mississippi Valley area. Elsewhere the loess formations have valley relationships. All valleys which carried valley trains of proper texture and which had sufficient width for the sweep of winds

are bordered by loess deposits, thicker on the bluffs than away from them and extending greater distances on the uplands on the leeward sides than on the windward.

WISCONSIN LOESS DEPOSITS OF ILLINOIS

The Wisconsin loess deposits of Illinois have received intensive study by both the State Geological Survey and the State Soil Survey. As a result the distribution, mode of occurrence, stratigraphic succession, thickness, properties, and weathering aspects are well known, and their origin as eolian products is well established.

Because loess deposits constitute the parent-soil materials of most of Illinois, about twenty years ago the State Soil Survey undertook a systematic investigation of the thickness of these deposits on uneroded or slightly undulating topography by making borings and excavations and by observing road cuts and other exposures. After some ten years of effort this work resulted in one of the most remarkable maps thus far made of loess deposits (fig. 4).

Attention has already been called to the fact that the northeastern part of the state has little loess and also to the fact that the loess west and south of the Wisconsin terminal moraine is thicker than that lying on contiguous portions of the Wisconsin drift. The latter is due to the time of incursion of Wisconsin ice in northeastern Illinois. This was after the Farmdale loess had been deposited and slightly weathered and after some Iowan loess had been deposited.

Even a cursory examination of this map indicates that the loess deposits of Illinois bear a genetic eolian relationship to the major valleys. Along the Mississippi, Illinois, Wabash, and lower Ohio valleys the loess attains its greatest thickness, thinning with distance from these major valleys. Furthermore, the loess reaches its maximum thickness on the lee sides of the valleys and where the valleys are widest. This confirms the concept of T. C. Chamberlin (1897), which he set forth more than fifty years ago, that the aggradation of valley floors by valley trains of fine outwash gives rise to silt-covered flats, which, upon subsidence of glacial floods in the fall, become subject to sweeping winds, resulting in the transfer of large quantities of silt over the adjoining uplands. This process continues up to the end of valley-train filling, when vegetation reclothes the valley floor, and ends the loess episode.

Chamberlin also pointed out that the extent and amount of the eolian deposits are a function in part of the width of the valley-train flat exposed to the winds and the trend of the valley train with respect to wind direction. Figure 4 illustrates clearly the principle of valley width and loess thickness. In Hancock County of western Illinois, where the Mississippi Valley is narrowest, the loess reaches scarcely 12 feet in thickness, whereas to the north and south, where the valley is wider, the loess attains a thickness more than twice as great. East of the wide American Bottoms near St. Louis the loess is about 70 feet thick.

That there would be as many loess episodes as valley trains would be contingent largely upon the texture of the valley-train material. The number along the Illinois Valley during the Wisconsin glacial stage is believed to have been four—Farmdale, Iowan, Tazewell, and Cary. The number along the Mississippi Valley may have been one more, the Mankato, but the evidence for this is mainly the existence of sand dunes on sandy terraces of Mankato age.

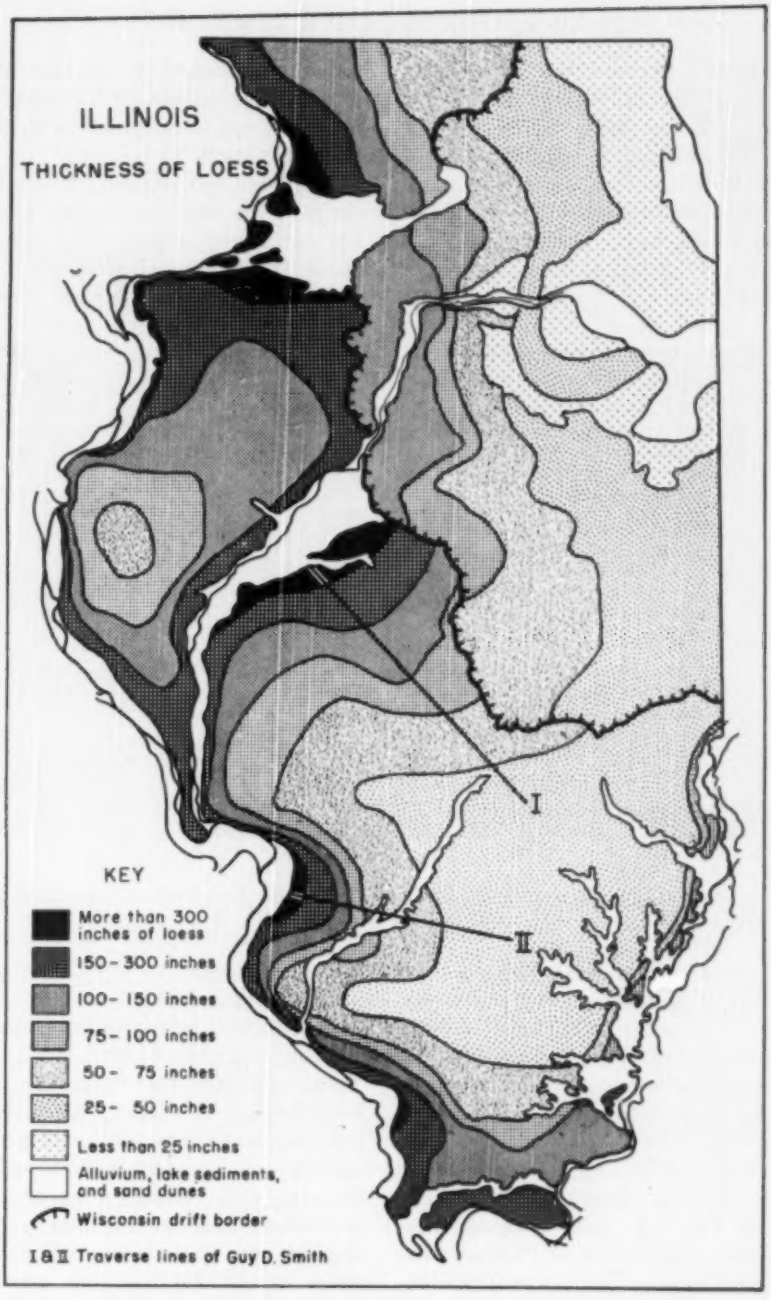


FIG. 4.—Approximate thickness of loess on uneroded topography in Illinois. Modified from map by University of Illinois Soil Survey (Smith, 1942, fig. 3, based on data collected by R. S. Smith and E. A. Norton and by others).

In places the color of the loess reflects the color of the valley-train silts. Below Havana, Illinois, some of the loess is pink, corresponding to the pink color of some of the silt of the Tazewell outwash.

Physical and chemical studies of the Illinois Valley loess.—Smith (1942) has made a very detailed and illuminating study of Illinois Valley and Mississippi

dunic but composed of dust that settled out of the atmosphere, each of these loess formations has a mathematical form and is a unit in itself.

Smith obtained samples from the basal fourth of the loess, containing primary carbonates and representing approximately the same geologic horizon, and subjected these to mechanical analysis.

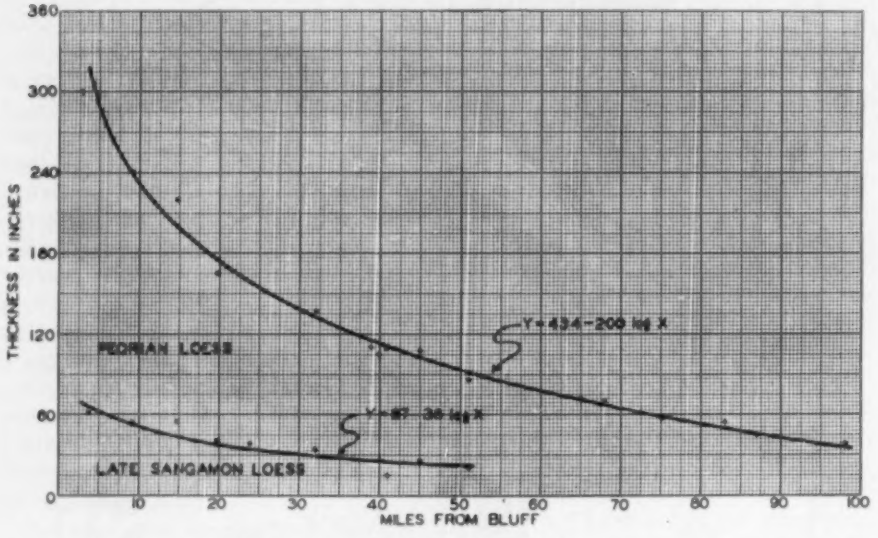


FIG. 5.—Variations in thickness of Peorian and Farmdale (labeled "Late Sangamon") loess with distance from bluffs, traverse I, shown in fig. 4 (Smith, 1942, fig. 6).

Valley loesses, the former along a traverse extending a distance of nearly 100 miles from a point on the bluff in Menard County, where the loess is thickest, to Effingham County. This line transects at right angles the belt of thickest loess (fig. 4).

The two curves in figure 5, copied from Smith, show the rate of decrease in thickness of Farmdale loess (labeled "Late Sangamon loess") and of Peorian loess, with equations for the curves. The equations imply that, beginning about 3 miles from the bluff, where the loess is not

His graph of mean particle size with logarithm of distance from the bluff is shown in figure 6, and his graphs of 10–20 μ silt and 30–50 μ silt are given in figure 7. These data show that "the coarser fractions decrease in quantity, the finer fractions increase in quantity, and the intermediate fractions first increase and then decrease with distance from the bluff. Within limits there is a linear relationship between particle size and the logarithm of the distance from the bluff" (Smith, 1942, p. 153). The changes in particle size are rapid close to the bluff,

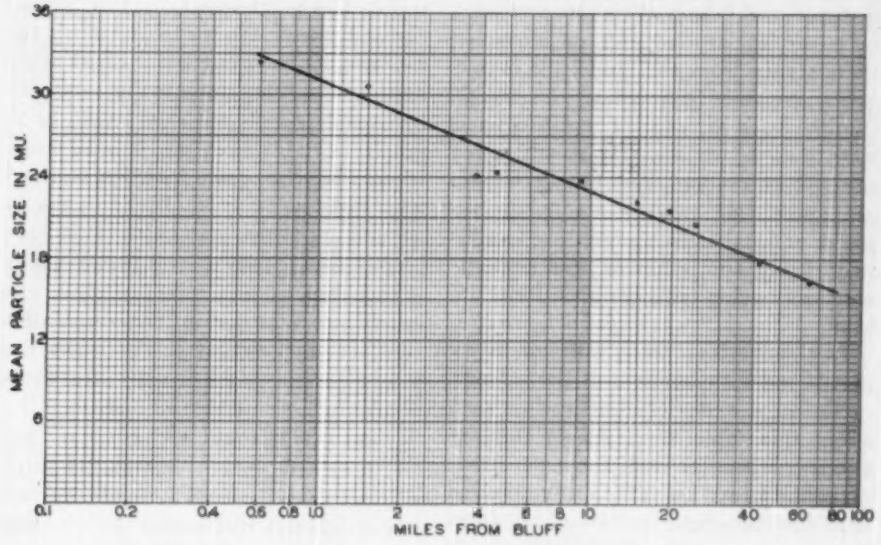


FIG. 6.—Variations in mean particle size of calcareous Peorian loess, with logarithm of distance from bluffs, traverse I (Smith, 1942, fig. 5).

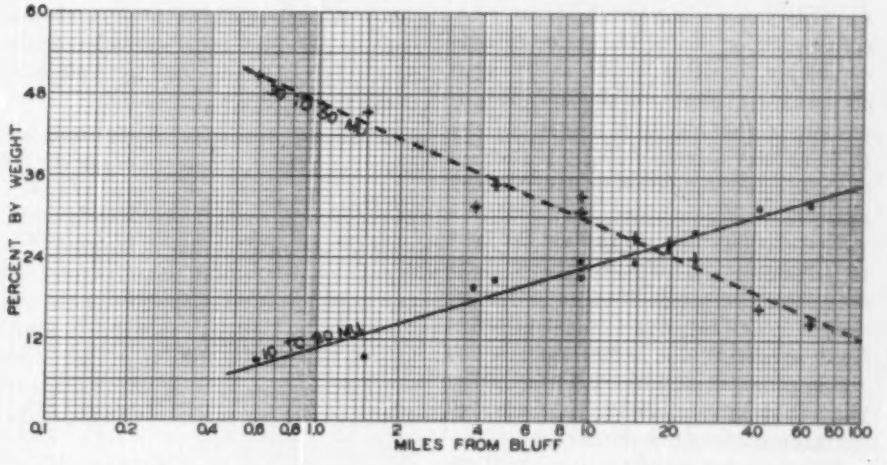


FIG. 7.—Variations in percentages of 10–20 μ silt and 30–50 μ silt in calcareous Peorian loess, with logarithm of distance from bluffs, traverse I (Smith, 1942, fig. 4).

and only small changes take place at a distance, and "the particle size decreases by a constant number of units whenever the distance from the bluff is increased by a constant percentage of itself" (Smith, 1942, p. 156). There are some variations in particle size at any place selected at random, but the variations are apparently random and show no trend, and, taken as a whole, the loess is remarkably homogeneous, this homogeneity increasing with distance from the bluff.

Determinations were also made by Smith and his associates of the calcium carbonate content of the Peorian loess along this same traverse, on samples taken consistently from the lower quarter of the formation. This study revealed that the carbonate content of the loess decreases for every textural fraction with distance from the bluff and that the percentage loss is inversely proportional to the thickness of the loess formation (fig. 8). This can be accounted for only by active solution during the period of loess deposition. In other words, as the loess accumulated, there was a steady loss of calcium carbonate from leaching, and this loss was correspondingly greater as the rate of accumulation decreased away from the bluff.

Calculations indicate that, at the time of accumulation, Illinois Valley loess may have had a calcium carbonate content of somewhat over 41 per cent at the bluff, where it was some 1,100 inches thick, and 0 per cent where it was thinner than 80 inches and under forest cover or 50 inches under grass cover.

Some geologists (Russell, 1944*a*, pp. 2–5), in their attempts to define loess, have made calcium carbonate an essential component. In tracing the Illinois Valley loess away from the bluff to its recognizable limits, one is obliged to regard all of it as loess whether it accumulated as a calcareous or as a noncalcareous deposit. To try to demarcate the two areas on the basis that the part of the deposit which accumulated as a noncalcareous deposit is not loess would be to ignore its natural history. It is all windblown, but its characteristics changed with distance from the bluff because of attending physical and chemical factors.

The area of that part of Illinois which is underlain by loess that lost all its calcareous content during its accumulation cannot be determined with accuracy, but it is apparent that it is very substantial —over half of southern Illinois (fig. 4).

That this has been an important factor in bringing about the relative infertility of the soils of southern Illinois cannot be doubted. By the time the loess deposition had ceased, the profile of weathering of the thin loess was far advanced, while the profile of weathering of the thick loess near the bluff was in its infancy. Between these extremes there was every gradation. Smith's detailed analysis of this is recommended to all students of the loess (1942, pp. 172–173).

When the deposition of the loess had been completed, leaching began at the surface and proceeded downward. Waters do not move far in loess without becoming saturated. This is inferred from the narrow transition zone between the leached and the unleached horizons, usually not more than an inch thick. Smith has shown analytically that the uppermost few inches of the calcareous zone have as much carbonate as do the deeper portions (1942, p. 167).

The amount of post-loess leaching is commonly greater farther from the bluff than near, owing to the differences in the amount of carbonate present. Furthermore, the amount of post-loess leaching is

greater under forest vegetation than under grass vegetation. The average ratio of loss appears to be about 3 to 2 (Smith, 1942, p. 170).

Smith calculated the loss of calcium carbonate under forest vegetation since the close of the loess depositional period for measured determinations in Cass, Menard, and Sangamon counties and found that the average loss is equivalent to a layer of calcium carbonate particles 17.7 ± 0.5 inches thick. He has also computed the average leaching loss during the entire period of deposition and found it to be equivalent to a layer of calcium carbonate particles 29.8 ± 3.0 inches thick. These data indicate that the period of deposition consumed a longer period of time than did the subsequent period of weathering, assuming that the controlling factors affecting the rate of leaching remained fairly uniform.

Mississippi Valley loess east of St. Louis.—Smith studied the Mississippi Valley loess east of St. Louis in the same way that he did the Illinois Valley loess, along a traverse (marked *II* in fig. 4) extending from the bluff for 70 miles to the northeastern part of Jefferson County, across the area of maximum thickness. The samples, however, were taken from the lower sixth of the Peorian loess, instead of the lower fourth.

The values obtained are similar in kind to those already discussed for the Illinois Valley loess and need not be reviewed in detail. Suffice it to say that the loess averages finer, and thins more rapidly, than in the case of the Illinois Valley loess. The finer size may be due either to weaker winds or to finer-textured valley-train material (being farther downstream), or both. The loess deposit appears, however, to possess the same interrelated characteristics of a wind-blown loess formation that are distinctive for the Illinois Valley loess.

The stratigraphic succession is the same as for the Illinois Valley loess, namely, Farmdale loess overlain by Peorian loess, the former resting on weathered Illinoian drift.

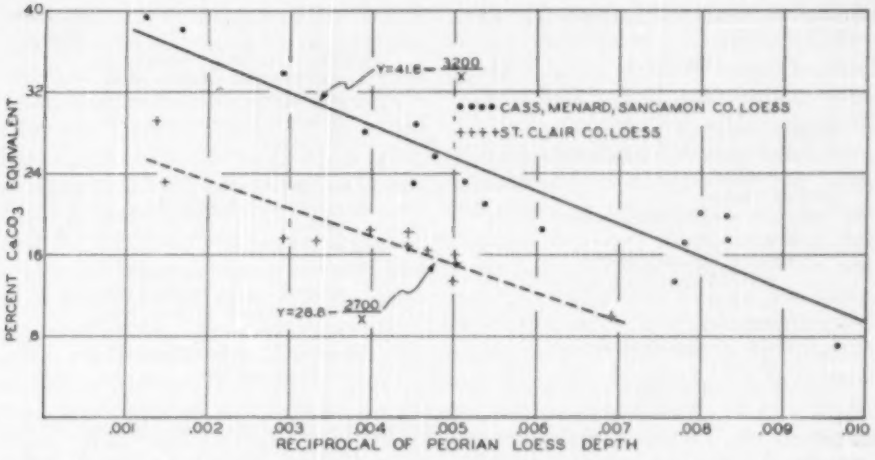


FIG. 8.—Calcium carbonate equivalent of Peorian loess as related to reciprocal of loess depth (Smith, 1942, fig. 11).

LOVELAND LOESS IN SOUTHERN ILLINOIS

The Mississippi Valley loess formations continue south to the Ohio River Valley, thicker along the eastern side than along the western, the same as farther north. Where the Illinoian drift of southern Illinois extends to the Mississippi River Valley, the succession of loess deposits also continues to be the same, namely, Farmdale loess overlain by Peorian loess, the Farmdale resting on weathered Illinoian drift. South of the Illinoian terminal moraine another loess formation, the Loveland, makes its appearance in the section beneath the Farmdale loess. As noted heretofore, the Loveland loess has a profile of weathering comparable to that of the Illinoian drift and appears to be pro-Illinoian.

TABLE 1

Units	Thickness (Feet)
Peorian loess, buff, leached	12
Farmdale loess, chocolate-brown, leached	12
Loveland loess:	
Horizon 2—compact, clayey	
Brown	2
Mottled buff and yellow, limonite stain on fracture surfaces	1
Ashen gray	1
Horizon 3—reddish-buff, clayey	3½
Covered to top of rock	3

The erosion of Sangamon times reduced the thickness of the Loveland, and weathering greatly changed its character. These factors and the burial of it by both the Farmdale and the Peorian loess obscure its presence, but several outcrops are available for study. An excellent, easily accessible exposure occurs above the Charles Stone Company quarry at White Hill in Johnson County, in the SW. ¼ of SW. ¼, Sec. 5, T. 14 S., R. 2 E., as shown in table 1.

INTRODUCTION OF EXTRANEOUS MATERIAL INTO LOESS

In an area of steep slopes, sand and pebbles from higher positions may become mixed with the loess, commonly in the basal portion. Organic agencies also contribute to the mixing, both on slopes and on flat uplands. An excellent exposure showing colluvial deposits in the Loveland, Farmdale, and Peorian loesses occurs west of Jonesboro, Illinois, in the SW. ¼ of SE. ¼, Sec. 21, T. 12 S., R. 2 W., as shown in table 2.

TABLE 2

Units	Thickness (Feet)
Peorian loess, buff, noncalcareous; at top is a rubble of angular Clear Creek chert, as in ledges exposed higher on the slope	20
Farmdale loess:	
Chocolate-brown	9
Same with scattered chert pebbles	4
Loveland loess:	
Horizon 2, reddish-brown, compact; angular chert rubble in lenses at top, scattered pebbles throughout	2½
Horizon 3, reddish-brown, without pebbles	3

LOESS DEPOSITS IN THE WABASH VALLEY

The same stratigraphic succession of loesses found along the Illinois Valley, a tributary of the Mississippi, also occurs along the Wabash Valley, a tributary of the Ohio. In the part of the Wabash Valley covered by Tazewell drift, north of Terre Haute, Indiana, Thornbury (1937) reports 5–8 feet of Tazewell loess, extending as far north as Williamsport, in Warren County, Indiana. The lower part of the loess is calcareous and overlies calcareous till of Tazewell age. Beneath the

Tazewell till, Thornbury reports Iowan loess 4–5 feet thick in Fountain County, 2–3 feet thick in Vermilion County, and 5–5½ feet thick in Vigo County, Indiana. In all exposures of Iowan loess it was calcareous to the top.

South of the Wisconsin drift the loess thickens notably, and the Iowan and Tazewell loesses, which have not been differentiated, are combined in the Peorian loess. According to Fidlar (1940), "the thicker and more extensive loess deposits on the upland south of the Shelbyville moraine are the result of an abundance of finer materials in the Wabash valley-train and in lacustrine deposits in tributary valleys." It may also be added that the Wabash Valley is much wider south of the Shelbyville moraine, affording a greater sweep for the winds, and that the addition of the Iowan loess accounts for some of the increased thickness. Although as much as 20 feet of loess are reported in Illinois on the western side of the Wabash Valley, the loess thins rapidly to the west and within 5–10 miles from the bluff line is less than 4 feet thick. On the eastern bluffs the loess is much thicker, and as much as 50 feet is reported.

Beneath the Peorian loess, typical Farmdale loess was observed by the writers on the hills 2½ miles north of Princeton, Indiana, near the center of Sec. 31, T. 1 S., R. 10 W., where a road cut exposes 12 feet of gray to yellow Peorian loess, the lower 7 feet calcareous, overlying 2 feet of pinkish-brown Farmdale loess, which contains only secondary carbonates.

An excellent section exposed on Highway 69 at the southern edge of New Harmony, Indiana, in the NW. ¼ of SW. ¼, Sec. 1, T. 5 S., R. 14 W., is shown in plate 1, *A*.

The distribution along the valley and the thinning away from it show clearly that the Wabash Valley is the source of the loess. Only wind transportation is adequate to explain its occurrence as a general topographic mantle, even on the glacial till of the highest hills, which rise more than 200 feet above the bottom lands.

Loess Deposits in the Lower Mississippi Valley

At the head of the lower Mississippi Valley, the Mississippi River is joined by the Ohio River, and both leave their confined valleys in Paleozoic rocks to enter a wide bottom land, eroded largely in the comparatively soft Tertiary and Cretaceous strata. As would be expected from differences in the bedrock, the eastern bluffs of the lower valley, to which this study has been largely confined, are not generally so high and steep as those along the upper valley south of the glaciated region, and the adjacent upland is more intricately dissected. The same stratigraphic sequence of loess formations continues, however.

Thick deposits of loess occur in the east bluffs as far south as a short distance south of the Louisiana state line (fig. 9) and also in Crowleys Ridge and Sicily Island within the valley. On the western bluffs thick loess also occurs at the head of the lower valley, but it thins southwestward. Loess appears to be generally present as far as Batesville, Arkansas, and scattered exposures were noted farther southwest to Little Rock, Arkansas. The writers also observed 5–6 feet of loess on the bluffs west of Sicily Island, near Rinehart, Louisiana.

In the belt of thick loess, numerous exposures, at least as far south as Natchez, Mississippi, show the Peorian, Farmdale,

and Loveland loesses with the same distinctive characteristics that they have in the upper valley. In 1948, Wascher, Humbert, and Cady differentiated the three loess sheets along the lower valley and described their physical and mineralogical composition. Many additional localities showing three loesses were observed in the present study.

In and near the bluffs the loess deposits generally rest on sand and gravel deposits, commonly called "Lafayette" or "Citronelle" gravel, which the writers consider to be preglacial but which Fisk (1938, 1944) and Russell (1940, 1944*a*) correlate with interglacial stages. At many places the upper surface of the gravels is deeply weathered, and, as it is overlain by Loveland loess, the weathering antedated the Illinoian. In other areas the Pliocene gravel and sand deposits were eroded before the loess was deposited, so that the loess rests on older Tertiary formations. Locally the loess rests on older Pleistocene valley-train material, such as the Natchez[5] formation in the vicinity of Natchez, Mississippi, and a similar formation near Vicksburg, Mississippi.

STRATIGRAPHY

PRE-LOVELAND (?) LOESS

Beneath the Loveland loess, remnants of a loesslike silt, which is usually chocolate-brown and noncalcareous, have been observed in several localities from northern Tennessee to Natchez, Mississippi, and on Crowleys Ridge near Wynne and

[5] The authors, after careful field study, have reached the opinion that the Natchez formation is a Pleistocene valley-train deposit, as interpreted by Chamberlin (1896), Chamberlin and Salisbury (1907, pp. 386–388), and Vestal (1942), and is separate from, and younger than, the Lafayette-type gravels, contrary to Fisk (1938, pp. 152–154).

PLATE 1

A, Exposure on State Highway 69 at the southern edge of New Harmony, Indiana, showing (*1*) 5 feet of leached Illinoian till, (*2*) 5 feet of calcareous, pinkish-brown Farmdale loess, and (*3*) 15 feet of calcareous, yellow-brown, fossiliferous Peorian loess. The color differences are more distinct in nature than in the photograph.

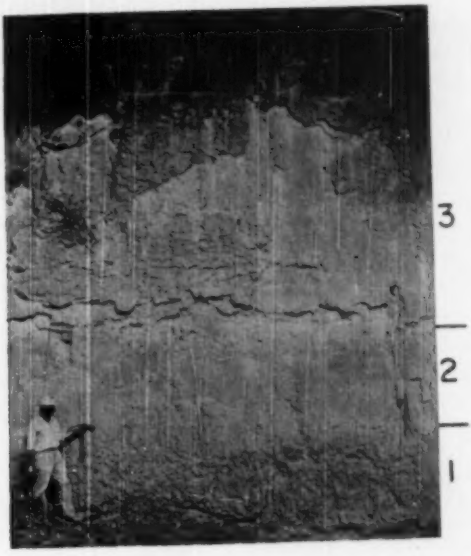
B, Exposure along road leading down Mississippi River bluffs to ferry at Columbus, Kentucky, showing (*1*) Lafayette-type gravel; (*2*) 6 feet of Loveland loess, consisting of a thin, light-weathering Horizon 1, which makes a re-entrant at the top, a Horizon 2, which is the darker band below, and a Horizon 3, which is approximately the lower half; (*3*) 7 feet of chocolate-brown Farmdale loess; and (*4*) buff Peorian loess.

PLATE 2

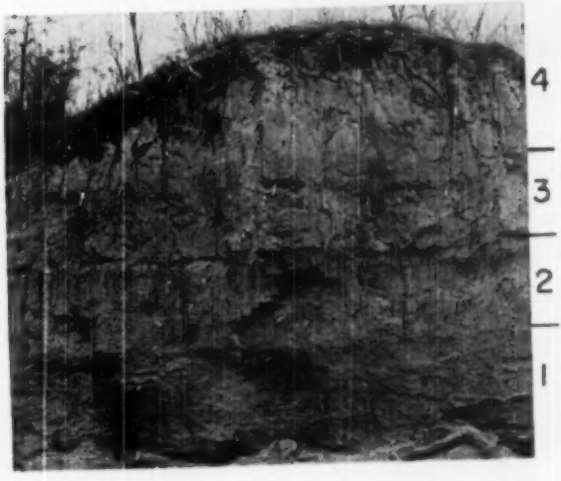
A, Exposure in deep, active ravine in Mississippi River bluffs, $1\frac{3}{4}$ miles northwest of Unionville, Tennessee, showing (*1*) 11 feet of Loveland loess, consisting of Horizon 1, 6 inches of gray silt forming a re-entrant at the top, Horizon 2, 4 feet of red compact clayey silt, and Horizon 3 (pick head on top), 6 feet 6 inches of yellow clayey silt; (*2*) 9 feet 6 inches of noncalcareous, chocolate-brown Farmdale loess; and (*3*) 32 feet of buff to yellow-brown Peorian loess, the upper 16 feet noncalcareous (foreshortened in photograph).

B, Exposure along U.S. Highway 61 on the south side of Big Black River, 20 miles south of Vicksburg, Mississippi. The shovel-pick head (*arrow*) is on the top of 4 feet of Loveland loess, which is red to yellow-brown compact clayey silt, overlain by 6 inches to 2 feet of Farmdale loess, which is chocolate-brown silt, less calcareous than above, except for large concretions, overlain by 20 feet of buff calcareous Peorian loess, distinguished by its smooth, dark, moss-covered surface. The thinness of the leached zone on the Peorian, mostly covered by vegetation in this exposure, is characteristic of steep erosional slopes.

C, Typical road cut in Peorian loess, at Big Black River, 30 yards uphill from *B*, showing the contrast in weathering between the dark, moss-covered calcareous loess below and the lighter, leached loess above. On fresh surfaces the calcareous loess is the lighter colored. The diffusion banding in the upper 1–2 feet of the calcareous loess is characteristic of this zone.



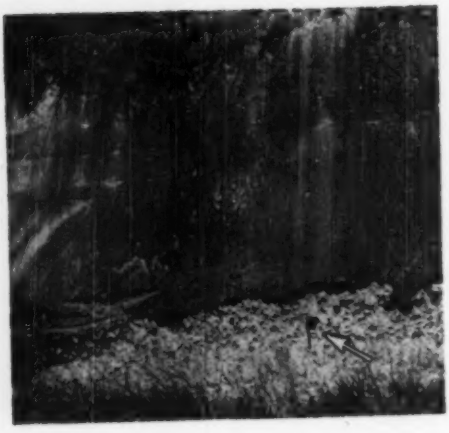
A



B

Loess exposures

A



B

C

Loess exposures

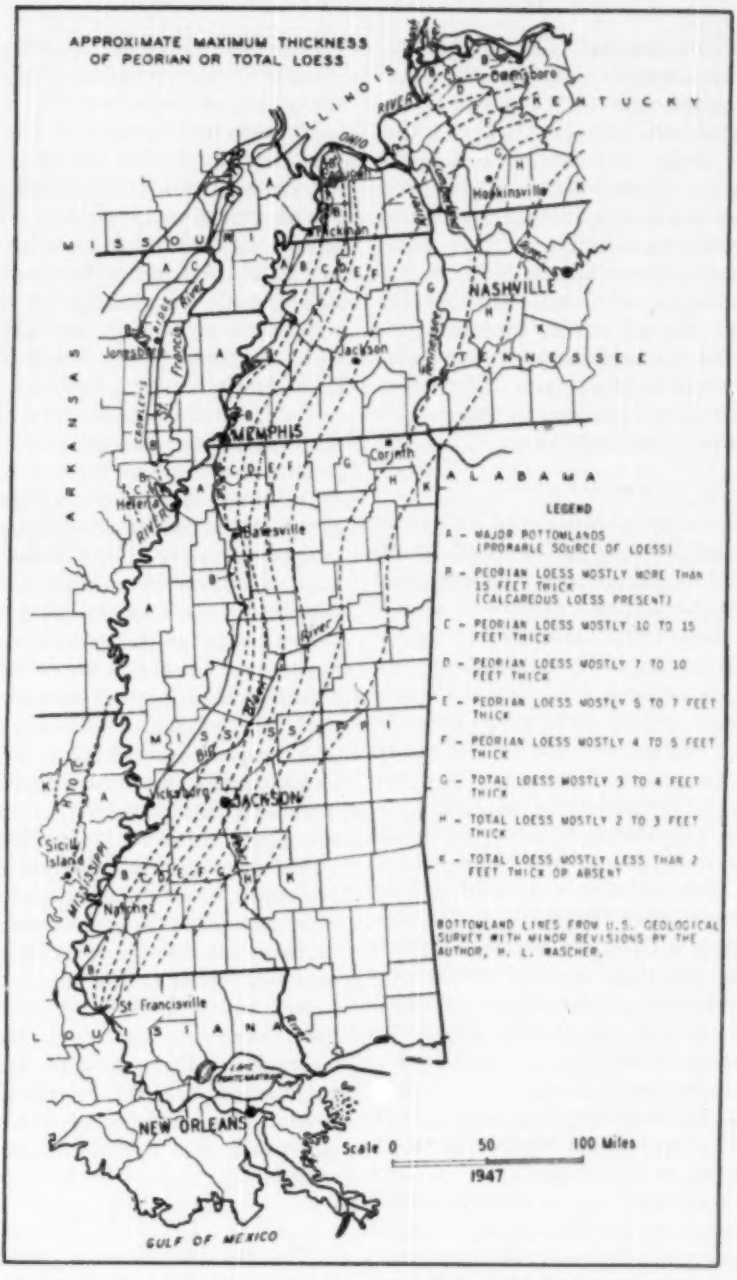

APPROXIMATE MAXIMUM THICKNESS
OF PEORIAN OR TOTAL LOESS
ILLINOIS
KENTUCKY
TENNESSEE
MISSOURI
ARKANSAS
MISSISSIPPI
LOUISIANA
ALABAMA
Cairo
Hopkinsville
NASHVILLE
Jackson
MEMPHIS
Corinth
Helena
Greenville
Vicksburg
JACKSON
Natchez
St Francisville
NEW ORLEANS
GULF OF MEXICO
Scale 0 50 100 Miles
1947
LEGEND
A - MAJOR BOTTOMLANDS (PROBABLE SOURCE OF LOESS)
B - PEORIAN LOESS MOSTLY MORE THAN 15 FEET THICK (CALCAREOUS LOESS PRESENT)
C - PEORIAN LOESS MOSTLY 10 TO 15 FEET THICK
D - PEORIAN LOESS MOSTLY 7 TO 10 FEET THICK
E - PEORIAN LOESS MOSTLY 5 TO 7 FEET THICK
F - PEORIAN LOESS MOSTLY 4 TO 5 FEET THICK
G - TOTAL LOESS MOSTLY 3 TO 4 FEET THICK
H - TOTAL LOESS MOSTLY 2 TO 3 FEET THICK
K - TOTAL LOESS MOSTLY LESS THAN 2 FEET THICK OR ABSENT
BOTTOMLAND LINES FROM U.S. GEOLOGICAL SURVEY WITH MINOR REVISIONS BY THE AUTHOR, H. L. WASCHER.

FIG. 9.—Thickness of loess in the lower Mississippi Valley (Wascher, Humbert, and Cady, 1948, fig. 1)

Forest City, Arkansas. They may represent a loess deposit older than the Loveland, possibly equivalent to the pro-Kansan loess locally found in the upper Mississippi Valley. It is best exposed in the Mississippi River bluffs in Natchez, where it is 4–8 feet thick, is overlain by Loveland loess which is as much as 15 feet thick, and overlies the deeply weathered zone on the Natchez formation. Locally an increase in clay content at the top of the silt suggests the presence of at least part of an illuvial zone (Horizon 2). Further study is needed to demonstrate that this is a separate loess.

LOVELAND LOESS

As in the upper Mississippi Valley, the Loveland loess is distinguished by its depth of weathering and the presence, at or near the top, of a prominent zone of clay concentration (Horizon 2)—a gumbo-like zone, 3–4 feet thick, which commonly is oxidized to a deep red but in places is reddish brown to yellowish brown. This soil profile is more advanced than the weathered zones on the Farmdale and Peorian loesses (pl. 1, *B;* pl. 2, *A*, *B*). The Farmdale shows almost no profile development below the Peorian other than oxidation and leaching of the carbonates, and the profile on the Peorian loess in the bluffs, although showing distinct zonation, has not reached the stage of advanced decomposition of primary silicates. As already shown, the profile of weathering on the Loveland loess is Sangamon in age.

Wascher and others (1948, p. 390) described the profile of weathering on the Loveland as consisting of an "A" horizon, a compact, light, brownish-yellow silt, 10–15 inches thick; a "B" horizon, consisting of red to yellowish-brown silty clay, the color varying with drainage conditions, 2½–3, locally 4, feet thick; and a "C" horizon, where the deposit was sufficiently thick, consisting of yellowish-brown to brownish-yellow silt.

The deep weathering of the Loveland loess is shown by the presence in it of only the most resistant minerals (Wascher and others, 1948, p. 393). In comparison with the Peorian and Sangamon loess (table 3), zircon and tourmaline are higher, epidote is greatly reduced, and hornblende and garnet are almost absent. The amount of feldspar is much lower, locally nearly a half lower.

The Loveland loess is entirely leached in all except one of about twenty-five exposures examined in the lower Mississippi Valley. In a cut along State Highway 3 at the crossroads at Crupp, Mississippi, the upper 4 feet of leached Loveland is underlain by 10 feet of calcareous fossiliferous loess, the base not exposed.

The maximum thickness of the Loveland loess observed is about 15 feet at Natchez, Mississippi. This does not include the 5 feet of silts beneath, which may be pre-Loveland. Near Unionville and Memphis, Tennessee, the Loveland is at least 10 feet thick (pl. 2, *A*). The average thickness of the Loveland in the various sections studied is about 5 feet. In general, the Loveland loess cannot be differentiated so far east from the valley bluffs as can the Farmdale loess. However, 2–4 feet of Loveland loess were observed about 6 miles east of the bluffs near Memphis, Tennessee, and near Batesville, Mississippi. Where it was originally thin, it lost its identity in the development of the Sangamon weathering profile on it and the underlying deposits.

FARMDALE LOESS

The Farmdale loess is readily differentiated in the area where the Peorian loess is 15 feet or more thick, a belt which

extends from the bluffs east between 5 and 15 miles. It can usually be recognized in a zone extending 5–10 miles farther east or until the Peorian loess is thinned to about 10 feet, in which area the Farmdale becomes nearly obscured.

Farmdale loess commonly overlies the prominent weathered zone of the Loveland loess, but, in places where the Loveland was presumably eroded before Farmdale time, the loess rests directly on relatively fresh to deeply weathered Lafayette-type sand and gravel or older Tertiary deposits.

Differentiation of the Farmdale from the overlying Peorian loess is made on the basis of color and leaching. The Farmdale loess is usually all noncalcareous and therefore is readily separated from the Peorian where the latter is calcareous. Where the Farmdale is thick, the lower part is calcareous and in places fossiliferous. At Samburg, Tennessee, the upper 3 feet 6 inches of the Farmdale are noncalcareous, and the lower 15 feet are calcareous. In places calcareous Peorian loess directly overlies calcareous Farmdale loess, but usually the Farmdale is less calcareous. Wascher and others (1942, p. 390) noted that near Finley, Tennessee, the Farmdale is 14 feet thick, calcareous, and fossiliferous.

Where thick and calcareous, the Farmdale loess has a distinctive pinkish-gray color. Where leached, it commonly is oxidized to a chocolate-brown color with a pinkish or purplish cast. It is readily distinguished from the lighter-colored buff Peorian (pl. 1, *B;* pl. 2, *A*). Although the Peorian becomes darker where it is thin and entirely leached, the Farmdale is still darker and frequently can be recognized in areas where it is only a few inches thick.

No zone of clay concentration from weathering was found in the top of the Farmdale, which is also true in the upper Mississippi Valley. Wascher and others (1948, p. 393) noted that mineralogically the Farmdale loess is similar to the C horizon of the Peorian (table 3). It appears to be more weathered than the calcareous Peorian but much less weathered than the B horizon of the Peorian.

North of Memphis, exposures of 10–20 feet of Farmdale loess are common near the bluffs. South of Memphis, the Farmdale is much thinner, and no exposure of more than 5 feet was observed (pl. 2, *B*). In the bluffs at Vicksburg and Natchez, where the Peorian loess is 75–100 feet thick, the Farmdale was 3 feet or less in all sections examined. Farmdale loess is also present west of the Mississippi River. It is 22 feet thick, calcareous and fossiliferous on the east end of Hickory Ridge, at Delta, Missouri, and at the head of the lower valley. On Crowleys Ridge as much as 7 feet of Farmdale loess was observed at Levesque, Arkansas, and 3–4 feet are present near Wynne and Forest City, Arkansas, and near Dexter and Advance, Missouri. Farmdale loess is also present on Sicily Island and was 4 feet thick in the one locality examined.

PEORIAN LOESS

The belt of hills along the eastern side of the Mississippi Valley, designated physiographically as the Bluff Hills section, in general identifies the areas where the Peorian loess is more than 15 feet thick. As stated above, the Peorian loess is 75–100 feet thick at Vicksburg and Natchez. The typical buff to yellow-brown loess which stands with nearly vertical faces in road cuts and excavations throughout the Bluff Hills area is Peorian loess (pl. 1, *B;* pl. 2). It is essentially the same as the Peorian loess in the upper Mississippi Valley in composition,

topographic position, stratigraphic relations, and general appearance.

The only apparent differences are in the depth of leaching, which increases southward from about 4 feet in northern Illinois to 15–20 feet in much of the lower Mississippi Valley, and in a stronger reddish cast of the weathered zone toward the south. This is believed to be a reflection of differences in climate. The increase in the depth of leaching of carbonates southward may be accounted for largely by the increase in rainfall and much longer seasons of unfrozen ground southward, as against decrease in solubility of the carbonates with increase in temperature.

As in the upper Mississippi Valley, the Peorian loess forms a continuous sheet, which mantles the eroded surface of older deposits at all elevations from the lowest terraces to the highest hills. Although the original loess sheet is now deeply eroded, a reconstruction by Wascher and others of the approximate original thickness by measurements in uneroded areas shows that the loess thins progressively eastward until, 50–75 miles from the bluffs, it is only about 2 feet thick (fig. 9). As the depth of leaching exceeds 15 feet, all the loess in the area east of the 15-foot isopach is noncalcareous. The typical calcareous bluff-type loess was found only in the area where the loess is more than 15 feet thick. Fossils are commonly abundant.

TABLE 3

MINERAL ANALYSES OF LOESS SECTION, OBION COUNTY, TENNESSEE*

MINERALS	PEORIAN			FARMDALE	LOVELAND
	B Horiz. Depth 2½ Ft.	C Horiz. Depth 7–7½ Ft.	Depth 10½–11 Ft.	Depth 12–15 Ft.	B Horiz. Depth 18–19 Ft.
Quartz†	90	83	78	88	95
Feldspar†	9	16	21	12	5
Heavy minerals‡	2.46	3.04	4.34	2.70	1.55
Hornblende§	8	16	20	11	0
Garnet§	Tr.	3	2	3	0
Epidote§	33	25	20	30	10
Zircon§	7	7	5	4	10
Tourmaline§	7	6	3	3	8
Titanium minerals§	12	10	6	14	32
Opaque minerals§	35	19	25	22	35

* 0.05–0.02 mm. fraction; data from Wascher, Humbert, and Cady (1948, p. 391).
† Per cent by volume, light fraction.
‡ Per cent by weight.
§ Per cent by volume, heavy fraction.

It is evident from the demonstration by Smith in the upper Mississippi Valley, previously described, that, because of the slow rate of deposition, the thinner deposits away from the valley were leached during the period of accumulation and therefore, unlike the thicker loess in the bluffs, had no carbonates when deposition ceased.

Mineralogically the calcareous Peorian loess commonly consists of 50–75 per cent quartz, 20–25 per cent feldspar, 15–30 per cent calcite and dolomite, 5–15 per cent clay, and 1–3 per cent heavy minerals (table 3). The weathered Peorian loess, however, in the B horizon con-

tains only 10–15 per cent feldspar, and most of the grains are cloudy and corroded. Hornblende, which forms 20–40 per cent of the heavy-mineral suite in the calcareous loess, is reduced to 1–10 per cent. The amount of garnet is considerably reduced. Epidote shows only a slight decrease. Zircon, tourmaline, and other resistant minerals become relatively more abundant.

Wascher and others (1948, pp. 397–398) noted the same general variation in the weathering profile which Smith described in the upper valley: a relatively weak profile differentiation on the thick, highly calcareous Peorian at the bluffs and a progressively greater differentiation eastward to a well-developed profile in the area of thin loess. As the major accumulation of loess in the lower valley probably had ended in Cary time, the present soil profile has been developing since that time. It is present throughout the loess-covered region, on both summits and slopes, and has reached the same stage of development at corresponding distances from the bluff. In other words, the Peorian loess forms a mantle over the whole topography and, whether high or low, is a time stratigraphic unit.

In contrast, Russell (1944*a*, pp. 5, 32) considers as loess only those deposits which are calcareous, although he accepts the absence of carbonates in the silt directly above calcareous loess as the result of weathering, which he calls "deloessification." His loess, therefore, is confined to the part of the Peorian loess area of the present authors where it is 15 feet or more thick, i.e., where the Peorian loess is sufficiently thick that it has not been entirely leached.

Russell does not differentiate the Loveland, Farmdale, and Peorian loesses or recognize any vertical sequence by superposition (1944*a*, p. 10). Believing the loess to be derived from backswamp deposits, Russell (1944*a*, pp. 30–32) relates it to what he (1940) and Fisk (1938, 1944, various cross-sections, pls. 4 and 26) call Williana (Aftonian), Bentley (Yarmouth), and Montgomery (Sangamon) fluviatile "terraces." Russell regards the loess on these respective "terraces" and on their erosional slopes as having required a long time to form by loessification, and hence the respective derivatives postdate their genetic materials. According to Russell, time has not been sufficient for loess to be formed from the Prairie terrace materials whose age is assigned to the "Peorian interglacial stage," which followed Fisk's (1944, fig. 75) "Early Wisconsin (Iowan)." It will be noted that these time divisions of the Wisconsin glacial stage are not those which have been widely accepted and which are based on the stratigraphy of the glaciated area (fig. 2).

Since the loess associated with their Williana terrace, according to their view, began to be formed before the loess from the Bentley terrace, and the loess from the Bentley terrace before that from the Montgomery, their profiles of weathering, or "deloessification," should differ. The present writers could discover no difference.

ORIGIN OF LOWER MISSISSIPPI VALLEY LOESS

As already indicated, the present authors have observed that the loess deposits of the lower Mississippi Valley are continuous stratigraphically with those of the upper; that their character and properties are similar to those of the upper; that they are similar as formational entities to those of the upper; that their valley relationships are like those of the upper; and that their respective profiles

of weathering resemble in stage of development those of the upper.

The eolian theory of origin and the modifications induced by contemporaneous and subsequent weathering fully account for all these phenomena as no other hypothesis does.

Under the loessification theory the topographic position of any loess derived from backswamp deposits would be lower than the parent-material. Therefore, there should be no loess on the oldest and highest "terrace" surface. Calcareous loess does occur on the highest surfaces, and on prominent isolated hills many miles removed from any hypothetical source of backswamp deposits.

Likewise, under the loessification theory the loess, being of colluvial origin, should be chiefly a slope phenomenon. Russell (1944*a*, pp. 10–11), therefore, minimizes the volume of the loess. New borings on the uplands, in areas where very substantial thicknesses of loess were inferred on the basis of the eolian hypothesis many years ago, confirm those inferences.

In support of the loessification theory, Russell (1944*a*, pp. 14–16) cites several localities where the transition from backswamp deposits on the "terraces" to calcareous loess at the base of the slopes can be observed. The localities described at Hickman, Kentucky; near Tiptonville, Dyersburg, and Memphis (Shelby Forest), Tennessee; and between Banks and Eudora, east of Greenwood, between Crupp and Anding, at Vicksburg and at Natchez, Mississippi, were examined in the present study. Although some of these sections are now in part overgrown, the exposures at Hickman, Memphis, between Banks and Eudora, between Crupp and Anding, and at Natchez were excellent.

In all these localities the deposits at the top of the section described by Russell as backswamp deposits cannot be differentiated megascopically from the silt in the leached zone, where it directly overlies calcareous loess and is accepted by Russell as weathered loess. No evidence of stratification or textural variation to suggest water deposition was found in any of the deposits described as backswamp deposits by Russell or in scores of similar sections scattered throughout the region. The degree of weathering is not adequate to destroy completely evidence of original bedding, except possibly in the upper 2–4 feet of the deposits, and even here that would probably not be universally true.

Several sections described by Russell were studied by the present writers to determine whether or not the calcareous loess exposed in the lower parts of the sections graded up the slope into a backswamp deposit. These transitions up the slope proved in all cases to be the normal transition from calcareous loess to leached loess. The leached zone thins down the slopes as the result of slope erosion.

At Hickman, Kentucky, between Banks and Eudora, and between Crupp and Anding, Mississippi, fresh road cuts and gullies demonstrated clearly that calcareous fossiliferous loess extends beneath the deposits described by Russell as backswamp deposits and beneath the highest surfaces in each locality. In other localities the presence of calcareous loess beneath the leached material described as backswamp deposits was established by augering. In all these sections in the lower valley, as well as those in the upper valley, there is no vertical change in character except that imposed by weathering. So far as the writers could determine, there is no basis for interpreting the material described by Russell as a

backswamp deposit as other than the weathered zone on the Peorian loess.

A comparison of the soil profiles developed where typical calcareous loess is known to occur below and on deposits which Russell describes as backswamp deposits shows (1) that the calcareous loess is the unaltered parent-material of the soil and not a younger deposit, as required by loessification; (2) that the silt described as a backswamp deposit can be no older than Wisconsin, and therefore not Sangamon, Yarmouth, and Aftonian silts on the three "terrace" surfaces, as differentiated by Fisk (1944); and (3) that the silt described as a backswamp deposit on all three "terraces" is of the same age even at levels 200–250 feet apart. Therefore, the silt cannot be a backswamp deposit.

From the viewpoint of composition, other major objections to the derivation of the calcareous loess from the weathered silts follow: The carbonates in the loess are primary because (*a*) they occur as discrete grains, (*b*) they are too uniformly distributed to be secondary, (*c*) they decrease in amount progressively back from the bluffs, and (*d*) they include grains of dolomite. Available evidence on the deposition of dolomite indicates that dolomite leached from the higher deposits would not be redeposited as secondary dolomite lower in the deposit. The distinctly secondary carbonates, such as concretions and fracture or root coatings, are calcite, even where the primary carbonates are highly dolomitic.

The abundance of feldspar, hornblende, and garnet in the calcareous loess is not compatible with derivation of the calcareous loess from leached silts because weathering greatly reduces these minerals in amount (table 3). Much of the feldspar remaining in the weathered silts is cloudy and corroded. Therefore, the weathered silts could not be the source of the silt in the calcareous loess because the latter contains fresh feldspar.

Erroneous Interpretations Originating from the Loessification Theory

The leached loess, described by Russell as a backswamp deposit, has been interpreted by Fisk (1944, pp. 15, 63) as being the fine-grained upper part of a depositional sequence grading downward into Lafayette-type sand and gravel at the base. However, instead of a gradation, there are horizontal zones of weathering separating a succession of loesses above the sand and gravel section and also in many places separating the loess from the underlying Lafayette-type gravel. Furthermore, there is a hornblende-garnet-epidote heavy-mineral suite in the loess deposits in contrast with a kyanite-staurolite-zircon suite in the underlying sands and gravels. The heavy-mineral suite in the loess deposits is the same as the heavy-mineral suite in the glacial valley trains, and the heavy-mineral suite in the Lafayette-type sands and gravels is the same as that in older Tertiary deposits. This was observed not only by the present authors but independently by Doeglas (1949).

Meander patterns have been mapped in some loess-covered areas, suggesting the water-laid origin of the loess (Fisk, 1944, p. 70, fig. 79; Russell, 1944*a*, p. 13). However, the channels referred to are clearly instances of reflection through the loess of pre-loess drainage lines. The water-laid deposits beneath the loess are much older than the loess, were deeply eroded before deposition of the loess, and consist of gravel and sand with little silt.

On the basis of the loessification theory, Russell (1940, p. 1214; 1944*a*, pp. 12–14) and Fisk (1944, p. 63, pl. 26; Fisk

and others, 1949, pls. 1–5) correlate the older alluvial surfaces west of the Mississippi Valley, in central Louisiana, with "terrace" surfaces on thick loess on the eastern side of the valley. Thereupon, Fisk (1939, 1944, pp. 69, 70, fig. 77) erroneously draws structural contours and develops an incorrect plane of reference for diastrophic interpretations.

The erroneous interpretation of the highest deposits of loess as derived from higher alluvial silts has led Russell (1940, pp. 1213–1227) and Fisk (1944) to postulate Pleistocene alluviation much wider than the present Mississippi Valley, an uplift of 300 feet since the Aftonian interglacial stage, and even a greater depth of valley-cutting.

The Environmental Factors of Loess Deposition by Wind

The climate during the time when winds were blowing silt from the glacial valley trains to form loess deposits on the bluffs and uplands varied from periglacial near the ice front to temperate farther south, though slightly cooler than the present. Large, thick snail shells are not present in the loess of the Illinois River Valley for some 70 miles from the Tazewell ice front, but small shells are common.

Wind directions also were variable, as at present, but in the main were westerly. The major loess accumulations occurred during the fall when the wind was predominantly from the northwest and relatively low rainfall permitted drying of the silts on the floodplains. Near the mouth of the Mississippi Valley the predominant direction of the wind was from the southwest.

The faunas indicate that rainfall and temperature were adequate to support a forest-type vegetation near the valleys and prairie vegetation on some of the relatively flat uplands, especially in the upper Mississippi Valley.

Repeated flooding of the bottom lands, resulting from progressive aggradation, served both to replenish the supplies of silt and to restrain the growth of vegetation. Fine outwash containing appreciable quantities of silt was an essential factor. Loess occurs in negligible amounts along valleys having coarse gravel outwash or an excessive amount of clay. In the lower Mississippi the most favorable sources of silt were along the major courses of the river, where the coarser silt and sand accumulated, rather than in those parts of the bottom land where the clay fractions serve to bind the sediments. Variations in these conditions probably account for some of the regional variations in thickness of the loess.

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AUTHIGENESIS IN WEST VIRGINIA SANDSTONES[1]

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ABSTRACT

The authigenic minerals in the Oriskany, Berea, and Big Injun sandstones are quartz, calcite, dolomite, orthoclase, microcline, albite, chlorite, kaolinite, and pyrite. Most of the quartz grew in open spaces, but some replaced clastic calcite. Two stages of silicification occurred in parts of the Berea sandstone. Authigenic chlorite appears as fringes around the detrital grains or around the early quartz growths. Calcite occurs as secondary rims on clastic calcite and as a cementing material in the voids. Rhombs of dolomite occur in the interstices and as replacements of feldspar and the clayey matrix. Authigenic feldspar is present in the form of overlays around detrital grains. Secondary kaolinite occurs as an alteration product of feldspar and as a filling in many of the voids which remained after the crystallization of the other minerals.

Most of the authigenic minerals formed after burial, because the secondary growths are generally free of strain and fill the cracks in fractured grains of mica and feldspar. The secondary calcite and chlorite probably formed from primary constituents in the sediments. Most of the silica was apparently derived from outside sources because little solution of quartz occurred at the points of contact between the detrital grains.

INTRODUCTION

This study of authigenic minerals was undertaken in order to obtain information on the processes leading to the cementation of oil- and gas-producing sandstones of West Virginia. Approximately seventy-five thin sections of outcrop and well samples of the Oriskany, Berea, and Big Injun sandstones were examined. The Oriskany sandstone is of Devonian age, and the Berea and Big Injun sandstones are of Mississippian age. The well samples, which included cores and fragments blown from the wells, were from producing horizons in most cases. The specimens of the Berea sandstone that were studied came from wells in Kanawha, Lincoln, Boone, and Wood counties. Samples of the Big Injun sandstone were from Clay, Tyler, and Marion counties. The Oriskany specimens were from wells in Kanawha and Harrison counties and from outcrops in Grant and Pendleton counties.

GENERAL DESCRIPTION OF THE SANDSTONES

The Oriskany sandstone is composed largely of quartz and calcite with small amounts of chert and feldspar. On the average, 5–10 per cent calcite is present, although in the more calcareous sandstones calcite constitutes nearly 50 per cent of the rock. In contrast to the Berea and Big Injun sandstones, the Oriskany is remarkably free of argillaceous material.

Some portions of the Berea and Big Injun sandstones are fairly pure, but most samples contain chert, feldspar, mica, calcite, and argillaceous material, together with fragments of shale, siltstone, and quartzite. The average calcite content is 1–2 per cent, but a few specimens contain as much as 35 per cent calcite.

AUTHIGENIC MINERALS

The term "authigenesis," as used in this paper, refers to the growth of minerals which took place after the sediments had been deposited. This would include mineral growth occurring before, during, or after lithification and representing secondary growths around detrital grains as well as new growths in the pore spaces and within other minerals.

The common authigenic minerals which occur in the sandstones studied

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are quartz, chlorite, orthoclase, microcline, albite, calcite, dolomite, kaolinite, and pyrite.

QUARTZ

Secondary growths on detrital quartz grains were found in all but two of the specimens studied. In the sandstones which contain argillaceous or calcareous material the outlines of the original grains are commonly marked by a zone of tiny inclusions. In the purer sandstones the boundaries between cores and secondary rims are generally imperceptible because the surfaces of the detrital grains are free of foreign matter. The quartz enlargements are in optical continuity with the detrital core. No growths were observed on fragments of chert or finely granulated quartzite. Apparently, silica was readily precipitated only on quartz grains above a certain critical size. Most of the secondary quartz grew in pore spaces, but some of the quartz replaced calcite (pl. 1, *A*) and feldspar. Much of the quartz which grew freely into voids or replaced calcite is euhedral. Where quartz nearly fills the pore spaces, the rocks have an interlocking texture, and most of the growths are anhedral. In the sandstones containing considerable primary calcite or argillaceous material the quartz rims are small, but in the purer sandstones the outgrowths on some grains are as large as the detrital cores.

The secondary quartz generally grew most rapidly in the direction of the *c*-axis. In the sandstones which are not completely cemented, prismatic growths are conspicuous along the *c*-axes of the detrital grains (pl. 1, *B*). As many as eight small prismatic crystals may be seen on some of the larger detrital grains (pl. 1, *C*). It is not so apparent that differential growth has occurred in the tightly cemented sandstones, which have an interlocking texture; yet measurement shows that the enlargements are greatest along the *c*-axes of the detrital grains. In two samples of well-cemented

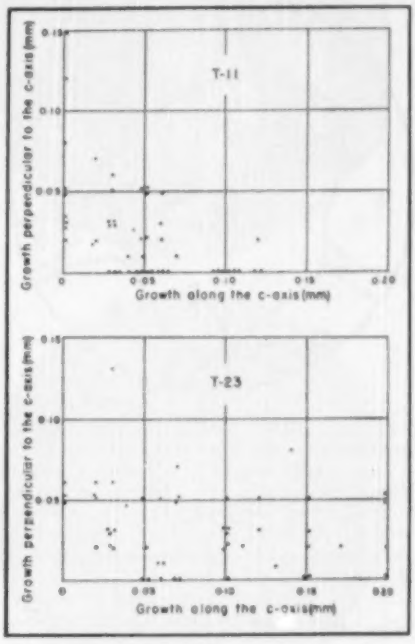

T-11
Growth perpendicular to the c-axis (mm)
Growth along the c-axis (mm)
T-23
Growth perpendicular to the c-axis (mm)
Growth along the c-axis (mm)

FIG. 1.—Relation between the widths of the secondary outgrowths along the *c*-axes (within 20°) of the detrital grains and the widths perpendicular to the *c*-axes in the Big Injun sandstone, Tyler County, West Virginia. Specimen T-11, 100 feet below the top of the Big Injun, thin section cut perpendicular to bedding. Specimen T-23, 120 feet below the top of the Big Injun, thin section cut parallel to bedding. Fifty grains measured in each section.

sandstone from the Big Injun the amount of growth was measured in the direction of the *c*-axis and in the direction perpendicular to the *c*-axis on fifty grains. Measurements in the two directions were made along lines passing through the center of the detrital core. The true growths along the *c*-axes, of course, can be measured only on grains

which are oriented with their *c*-axes in the plane of the thin section. In order to measure a significant number of grains in which the boundaries between the cores and outgrowths were clearly marked, grains were chosen in which the inclinations of the *c*-axes were within 20° of the plane of the thin section. Thus in some grains the growths measured were not exactly along the *c*-axes. Except for limiting measurements to favorably oriented grains with distinct outgrowths, the grains were chosen nonselectively. The positions of the *c*-axes were determined with a universal stage. In figure 1 the size of the growths along the *c*-axes (within 20°) are plotted against the growths perpendicular to the *c*-axes for the two specimens studied. In specimen T-23 the average growth along the *c*-axis (0.083 mm.) was 2.8 times larger than that at right angles to the *c*-axis (0.032 mm.). Out of fifty grains measured, thirty-six showed greater growth along the *c*-axis. The average diameter of the detrital cores in the grains measured was 0.3 mm. In specimen T-11, the growths along the *c*-axes were not so pronounced; nevertheless, twenty-eight out of the fifty grains measured showed greater growth along the *c*-axes. The average growth along the *c*-axis (0.048 mm.) was 2.1 times larger than that at right angles to the *c*-axis (0.023 mm.). The secondary enlargements in this specimen were smaller because the rock was finer grained and therefore the original pore spaces were not so large. The average diameter of the detrital

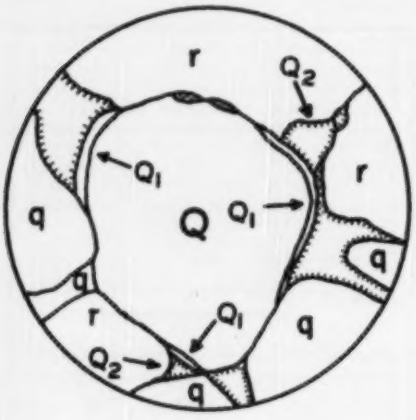


FIG. 2.—Tracing showing the two stages of quartz growth on quartz grain *Q* (pl. 1, *E* and *F*). The first-stage quartz growths are labeled Q_1 and the second-stage growths Q_2. Authigenic chlorite (*hachures*) grew after the first stage of quartz growth but before the second stage. The letter *q* indicates quartz grains, and *r* represents rock fragments of quartzite.

PLATE 1

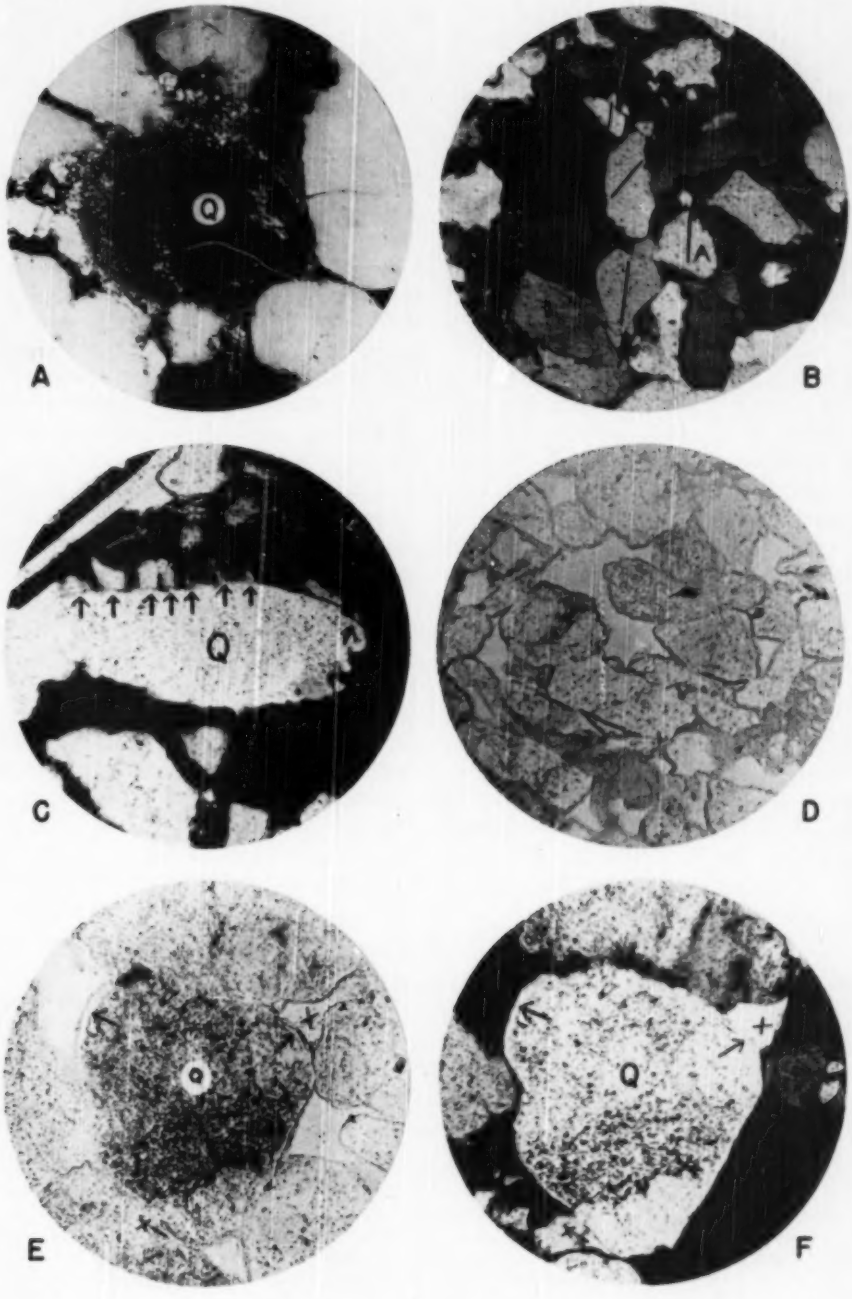
A, Big Injun sandstone. Detrital quartz grain (*Q*) in center of oölite, enlarged by outgrowth which partially replaced the outer portion of the oölite. Crystal faces are well developed on the secondary quartz except where other quartz grains have interfered with the growth. Crossed nicols, ×150.

B, Berea sandstone. Prismatic growths along the *c*-axes of quartz grains. Solid lines indicate the positions of the *c*-axes. These axes of the grains marked lie approximately in the plane of the thin section except for the grain labeled *A*. In this grain the *c*-axis is inclined about 30° to the plane of the section. Crossed nicols, ×60.

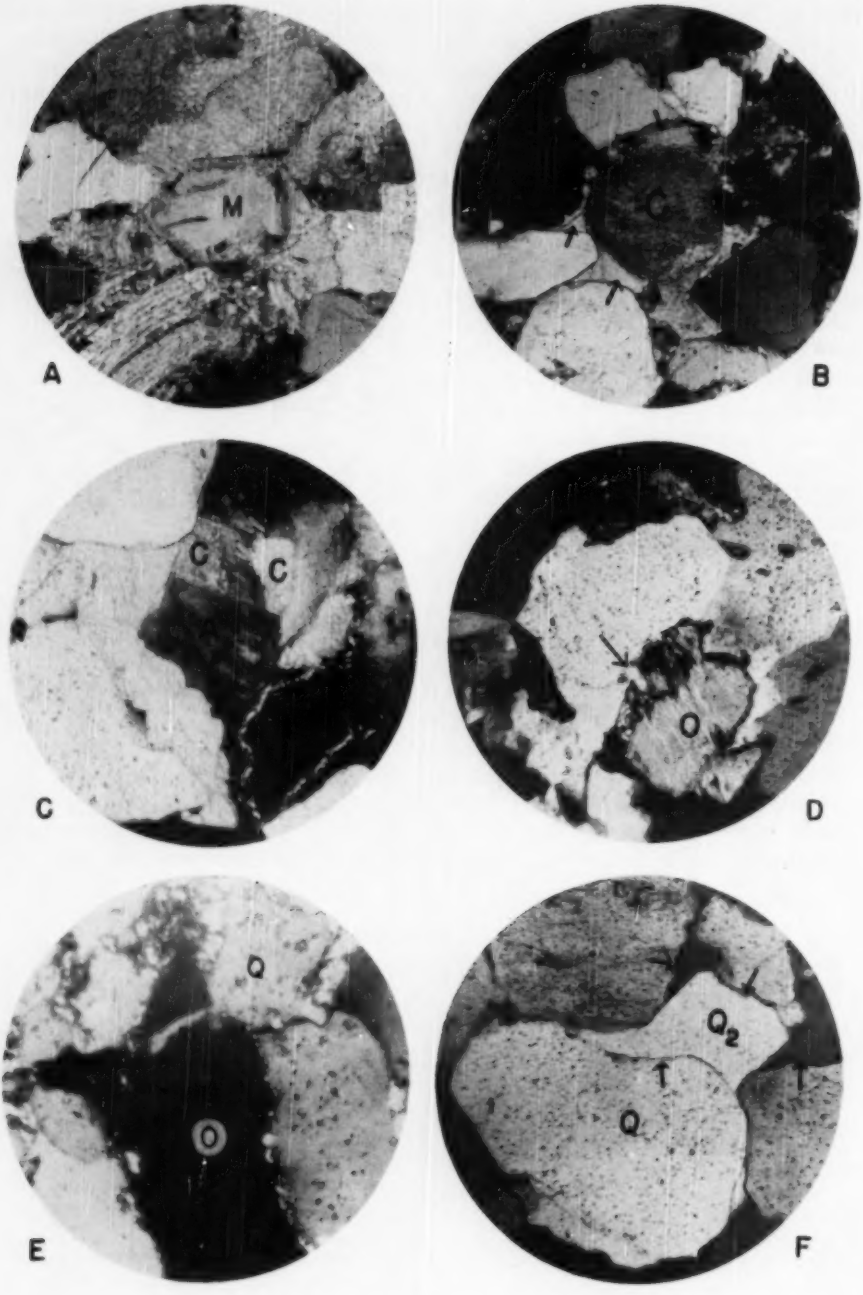
C, Berea sandstone. Eight prismatic quartz growths (*arrows*) have formed on grain *Q*. The long dimension of each growth is parallel to the *c*-axis of the quartz core, but the growths are not parallel to one another because the core has been strained and does not have the same crystallographic orientation throughout. Crossed nicols, ×120.

D, Big Injun sandstone. Detrital grains fringed with authigenic chlorite. The fact that the chlorite occurs on the free surfaces of the grains and not between grains indicates that it is secondary. Ordinary light, ×100.

E and *F*, Berea sandstone. Quartz grain (*Q*) showing two stages of secondary growth. The first-stage growths are indicated by arrows, and the second-stage growths are marked by crosses. Authigenic chlorite occurs as fringes on the first-stage growths (see also fig. 2). *E*, ordinary light, ×115; *F*, crossed nicols, ×120.



Big Injun and Berea sandstones



Oriskany, Big Injun, and Berea sandstones

cores of the grains measured was 0.19 mm.

These measurements show that there is a definite tendency for grains to become elongated parallel to the *c*-axes during secondary growth. The elongation of quartz grains along the *c*-axes in second-cycle sandstones, such as the St. Peter sandstone (Wayland, 1939), may have been due partly to secondary growth in the parent sedimentary rock. The shapes resulting from authigenic growth would probably be largely maintained even if the outgrowths were entirely worn off during transport.

In three specimens of the Berea sandstone it was found that the secondary quartz had grown in two stages (pl. 1, *E* and *F;* fig. 2). During the first stage of growth a thin film of silica, averaging 0.01 mm. in thickness, was deposited as a conformal envelope around the detrital quartz grains except where the grains were in contact. There was no tendency for crystal faces to develop during this stage of silicification. The fact that the growths form conformal envelopes around the detrital grains suggests that the precipitation of silica was relatively rapid. The silica apparently did not coagulate as a gel because it occurs only on quartz grains and shows no shrinkage cracks. Inasmuch as the surfaces of the growths tend to be smooth, they might be mistaken for rounded quartz enlargements from a pre-existing sediment. However, the rims are postdepositional because they are very uniform in thickness, with any indentations or projections on the detrital cores being reflected by corresponding irregularities on the outer side of the growths. Furthermore, the envelopes do not occur between grains or where the interstices are filled with argillaceous material. Although the secondary growths might have been removed between quartz grains as a result of pressure solution at the points of contact, the absence of rims where the quartz grains are in contact with soft minerals indicates that the rims are not predepositional. The conformal films of quartz are fringed with authigenic chlorite, which was deposited before the second period of quartz growth (pl. 1, *E* and *F*). The quartz which crystallized during the second stage in these specimens is similar in all respects to quartz growths in the other samples studied. The only specimens showing two periods of quartz growth were from the Berea sandstone in the Cabin Creek district, Kanawha County. The two-stage growths are apparently limited to the

PLATE 2

A, Oriskany sandstone. Microcline (*M*) enlarged by outgrowth which has replaced calcite. The enlargement contains tiny inclusions of calcite and is not in exactly the same optical orientation as the detrital core. Crossed nicols, ×120.

B, Big Injun sandstone. Clastic calcite (*C*) rimmed by secondary calcite (*arrows*). The secondary calcite is clear and forms an optically continuous mass. Crossed nicols, ×120.

C, Berea sandstone. Albite (*A*) partially replaced by calcite (*C*). Crossed nicols, ×120.

D, Big Injun sandstone. Lobe (*arrow*) of secondary quartz replacing orthoclase-microperthite (*O*). Boundary of the detrital quartz grain is faintly marked by tiny inclusions (*at head of arrow*). Crossed nicols, ×120.

E, Big Injun sandstone. Tongue of secondary quartz (*arrow*) from grain *Q* replacing orthoclase (*O*). Crossed nicols, ×220.

F, Berea sandstone. The second-stage quartz growth (Q_2) formed after chlorite because its surface is free of chlorite, although authigenic chlorite (*arrow*) occurs on the first-stage quartz growths or on the surfaces of the detrital grains where the first-stage quartz growths are lacking. In this specimen the first-stage growths are thin and not plainly visible in the photograph. Crossed nicols, ×120.

base of the Berea sandstone, but it is not known whether their occurrence is restricted to the Cabin Creek district because only two samples from the base of the Berea were available from other areas. These samples showed but one stage of quartz growth.

CHLORITE

An acicular, pale-green mineral believed to be chlorite is present in many samples of the Berea and Big Injun sandstones but is not found in the Oriskany sandstone. The authigenic chlorite occurs in all the Berea samples examined from Kanawha and Boone counties and is lacking in the samples from Lincoln and Wood counties. The distribution of chlorite in the Big Injun sandstone is irregular even within a given well.

The chlorite needles, which are a few microns long and less than 1 μ thick, normally occur as fringes around the other minerals (pl. 1, *D*). This chlorite is authigenic because it occurs only on surfaces of grains facing voids and not between grains. Furthermore, the chlorite has grown on quartz enlargements which formed during the first stage of silicification. Although the secondary chlorite generally constitutes only about 3 per cent of the rock, it completely lines those pores which are free of later authigenic minerals. Thus, even in many of the relatively pure sandstones, the nature of the pore walls is governed by the chlorite rather than by the quartz. The surface area of the chlorite itself is high because it occurs in the form of needles which are oriented approximately normal to the surfaces of the clastic grains. This may affect the yield of some reservoir rocks because of the greater retention of oil due to the increased surface area of the voids.

FELDSPAR

Authigenic feldspar has been observed in the Oriskany sandstone and in portions of the Big Injun sandstone which are free of argillaceous material. Although most of these sandstones contain considerable calcite, a calcareous environment is apparently not necessary for the formation of feldspar because some of the largest growths have occurred in sandstones essentially devoid of calcite. The secondary feldspar is commonly found as rims around detrital microcline or orthoclase and in a few cases around albite. The growths on microcline are either orthoclase (adularia) or microcline, whereas the rims on orthoclase and albite are of the same variety of feldspar as the core. The twinning in the detrital microcline continues into the outgrowths which are in optical continuity with the core. The enlargements on albite are untwinned. The crystallographic orientation of the secondary rims is generally not the same as that of the detrital grains and differences in extinction angles of 10°–15° are common. Although many of the detrital grains are perthitic, the outgrowths are, without exception, nonperthitic. In the calcareous sandstones the feldspar generally replaced the clastic calcite. Many of the feldspar rims are euhedral and contain numerous minute inclusions of calcite (pl. 2, *A*). Oölites and shell structures are commonly truncated by the secondary feldspar crystals. Few euhedral forms were exhibited by the feldspar outgrowths in the purer sandstones, apparently because their growth was impeded by the enlargement of near-by quartz grains.

CALCITE

Both primary and secondary calcite are present in most specimens, but the

relative amounts of the two types could not be precisely determined in all cases. Where the primary calcite is cloudy, owing to inclusions, or occurs in oölites and shells, it can readily be distinguished from the clear secondary calcite (pl. 2, *B*). In the samples containing authigenic chlorite the boundaries of the primary calcite are marked by fringes of chlorite. The bulk of the calcite in the calcareous sandstones is generally of clastic origin. Much of the clastic material is apparently crinoid debris and is rimmed by secondary calcite, which is in optical continuity with the core. In one calcareous sample of the Big Injun sandstone a large part of the calcite appeared to have been introduced. The specimen showed conspicuous "luster-mottling," with large calcite crystals averaging 1.5 mm. in diameter commonly enclosing over one hundred quartz grains. Where clastic calcite has recrystallized, the calcite crystals are generally smaller and enclose only a few quartz grains. Besides filling open spaces, the secondary calcite has replaced feldspar to a small extent in the Berea and Big Injun sandstones (pl. 2, *C*).

DOLOMITE

Small amounts of secondary dolomite are present in many specimens of the Berea and Big Injun sandstones. The dolomite has a rhombohedral outline and occurs as a filling in voids and as a replacement of feldspar and of shale fragments. Some chert fragments contain many small dolomite rhombs. This dolomite probably does not represent postdepositional growth because only a few chert fragments in a given sample are replaced by dolomite. The refractive indices of the carbonate in some specimens indicate that it is iron-bearing and in a few cases is actually ankerite.

KAOLINITE

An authigenic clay mineral thought to be kaolinite occurs in many specimens of the Berea and Big Injun sandstones but is lacking in the Oriskany sandstone. The kaolinite has an average refractive index of 1.565, is platy in habit, and occurs in mosaic-like aggregates. Some of the kaolinite fills pore spaces, but much of it is pseudomorphous after feldspar. Although the kaolinite generally is present in amounts less than 5 per cent, in some samples it comprises 10 per cent of the rock.

PYRITE

Small amounts of secondary pyrite were found in most samples. The pyrite occurs partly as an interstitial filling and partly as a replacement of detrital grains and the clayey matrix. Some larger pyrite crystals are euhedral and enclose several corroded detrital grains.

REPLACEMENT OF FELDSPAR

Although feldspar is stable in the Oriskany sandstone, as is evidenced by secondary outgrowths, it has undergone replacement by calcite, dolomite, quartz, or kaolinite in portions of the Berea and Big Injun sandstones. In some grains of feldspar the replacement is limited to slight corrosion along the margins; in others, the feldspar has been largely or completely replaced.

Feldspar has been more commonly replaced by calcite and dolomite than by quartz or kaolinite. Replacement by calcite generally started at the periphery of the feldspar grains, whereas many of the dolomite rhombs commenced their growth within the feldspar grain. In some cases, only isolated remnants of feldspar occur in a matrix of secondary calcite or dolomite. The fact that the remnants have a common crystallo-

graphic orientation indicates that they are actually unreplaced relics and not shattered fragments of feldspar which were later cemented by secondary carbonates. Sericitic streaks, which occurred along albite lamellae in grains of perthite, are left as unreplaced relics in the carbonates. Where the perthite has been only partially replaced, the sericitic streaks pass without interruption from the perthite into the carbonate. The authigenic chlorite fringes which encircled the feldspar grains are also left as unreplaced remnants in the carbonate replacements.

The quartz replacements are generally small. Some of the contacts between feldspar and quartz have a sutured appearance, with irregular projections of secondary quartz extending into the feldspar. The most convincing evidence of replacement by quartz is found where long narrow lobes of secondary quartz extend almost completely across the feldspar grains (pl. 2, *D* and *E*). The deepest penetrations are generally parallel to the lamellae in perthites. The perthitic feldspars appear to be more susceptible to replacement by quartz than do the homogeneous feldspars.

In some specimens of the Berea and Big Injun sandstones the feldspar has been kaolinized. All stages in the alteration may be observed, from slight corrosion at the margins to complete replacement. The feldspars altered directly to kaolinite without the formation of intermediate products. The unreplaced remnants of feldspar are fresh, and the contacts between the feldspar and kaolinite are sharp. In the rocks containing the most kaolinite, feldspar is completely lacking. Where a moderate amount of kaolinite occurs, some albite is normally present, but potash feldspar is lacking. Presumably, potash feldspar was more susceptible to kaolinization than albite under the prevailing conditions. Meteoric waters were perhaps responsible for the alteration of the feldspars to kaolinite.

The factors controlling the replacement of feldspar by carbonates and quartz are not apparent. The replacement was not controlled by depth of burial because the feldspars were altered in the shallow sediments as well as in the deeply buried sediments. In the sandstones which are free of argillaceous material the feldspars were stable, as is evidenced by secondary enlargements. In the argillaceous sandstones, however, the feldspars are commonly replaced. This suggests that the nature of the original sedimentary material may have been an important factor. In an aluminous environment sericite or illite might form at the expense of potash feldspar, although no direct sericitization of feldspar was observed. The occurrence of authigenic sericite in a clayey matrix would be difficult to detect. Because of the large number of variables involved, considerably more data will probably have to be obtained before all the factors controlling the stability of feldspar in sediments are known.

SEQUENCE OF CRYSTALLIZATION

The sequence of crystallization of the secondary minerals is the same in all the specimens studied. The quartz which forms thin, conformal envelopes around the detrital grains crystallized first. Authigenic chlorite formed next because it occurs as fringes on the early quartz envelopes and is not found on the other secondary growths. Where there were no early quartz envelopes, the chlorite was deposited directly on the detrital grains. The later growths of quartz, which are characterized by euhedral forms, crystal-

lized after the chlorite because the surfaces of these quartz enlargements are free of chlorite (pl. 2, *F*). Most of the secondary quartz formed during this stage rather than before chlorite.

The secondary calcite was deposited later than the authigenic chlorite, inasmuch as there is no chlorite on the surfaces of the calcite. Both the secondary calcite and the dolomite appear to have formed after the growth of quartz. The secondary quartz adjacent to authigenic calcite is free of carbonate inclusions and therefore probably did not replace the calcite but grew before calcite. On the other hand, the secondary quartz which formed by replacing primary calcite contains numerous calcite inclusions (pl. 3, *A*). Dolomite also formed after quartz, but the age relations between dolomite and calcite could not be ascertained.

Kaolinite, which is common in some specimens of the Berea and Big Injun sandstones, apparently was the last authigenic mineral to crystallize. It formed on the surfaces of the secondary carbonates and filled many of the interstices left after the growth of the other secondary minerals. Calcite and dolomite are intimately associated with kaolinite in the pseudomorphs after feldspar. Inasmuch as there is no evidence that the carbonates have replaced kaolinite either within the pseudomorphs or in other parts of the rocks, it is likely that the feldspar was partially replaced by the carbonates before the onset of kaolinization.

On the basis of the samples studied, the most probable order of crystallization of the common secondary minerals may be summarized as follows: (1) first-stage quartz growths (characterized by conformal envelopes around detrital quartz grains); (2) chlorite; (3) second-stage quartz growths and feldspar (euhedral growths on quartz common); (4) calcite and dolomite; and (5) kaolinite.

Evidence for each of the above periods of crystallization may be observed in a single thin section of a few samples of the Berea sandstone. In most of the rocks, however, some of the stages are not represented, although the order of crystallization of the secondary minerals which are present is the same in all cases.

TIME OF CRYSTALLIZATION

Several lines of evidence indicate that the authigenic minerals crystallized after burial and compaction of the sediments rather than penecontemporaneously with the deposition of the sediments, as suggested by Krynine (1940, pp. 111–113). Cracks which developed in grains of mica and feldspar, apparently as a consequence of burial, have been commonly filled with secondary minerals (pl. 3, *B*, *C*, and *D*). Some of the feldspar grains were completely shattered, and the resulting fragmental material was cemented by secondary quartz that is free of strain. In a few cases the cracks in the feldspar are filled with authigenic feldspar, which is nearly in optical continuity with the fractured grain (pl. 3, *E*). In the sandstones showing sutured contacts between detrital grains, the secondary quartz apparently crystallized after the grains had penetrated into one another (pl. 3, *F*). Presumably, conspicuous suturing would not form in unconsolidated sediments; therefore, the quartz must have grown after burial. Furthermore, the slender secondary quartz crystals which are commonly attached to the detrital grains would probably have been disrupted if they had grown before compaction of the sediments. It is generally believed (Pettijohn, 1949, p. 251) that authigenic chlorite forms during diagenesis and burial.

Inasmuch as chlorite grew before the other secondary minerals, with the exception of the conformal quartz envelopes, most of the secondary crystallization apparently occurred after burial. It is therefore possible that oil and gas entered the carrier beds before the onset of most of the secondary deposition.

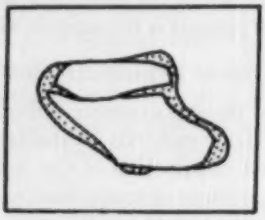


FIG. 3.—Tracing of microcline grain *M* in plate 3, *E*. The microcline was fractured and later cemented by secondary orthoclase (*stippled area*).

SOURCE OF THE CEMENTING MATERIAL

Inasmuch as evidence of hydrothermal alteration is lacking in these rocks, it seems unlikely that the cementing materials were derived from an igneous source. Although some of the constituents were probably present in the connate waters, much of the material apparently was introduced.

The secondary quartz which grew during the first stage of silicification and the authigenic chlorite probably formed from constituents originally present in the sediments. These growths were found only in the rocks which contained argillaceous material. Presumably, silica and hydroxides of iron and alumina were available in the original clay portion for the chlorite and early quartz growths.

Most of the silica which was deposited after the crystallization of chlorite appears to have been derived from outside sources. Solution of quartz at the points of contact of the grains, as proposed by Waldschmidt (1941, pp. 1859–1863) and Gilbert (1949, p. 14), does not satisfactorily account for the secondary silica in the rocks studied. Sutured contacts between quartz grains are lacking in the more highly silicified rocks, and there is no mutual penetration of the detrital grains. Although solution has occurred in a few rocks, as evidenced by sutured contacts, there appears to be no necessary relation between the amount of solution and the amount of secondary quartz in a given sample. In some specimens an appreciable amount of solution has occurred; yet secondary outgrowths are lacking. The amount of solution appears to have been adequate to account for the secondary enlargements in a few of the sandstones. However, deposition of silica occurred after and not during the

PLATE 3

A, Oriskany sandstone. Calcareous shell partially replaced by quartz outgrowth. The structure of the replaced shell is vaguely marked by rows of calcite inclusions within the secondary quartz. Unreplaced remnants of the shell occur between the grains (*arrows*). Borders of the detrital quartz cores are shown by dashed lines. Crossed nicols, ×130.

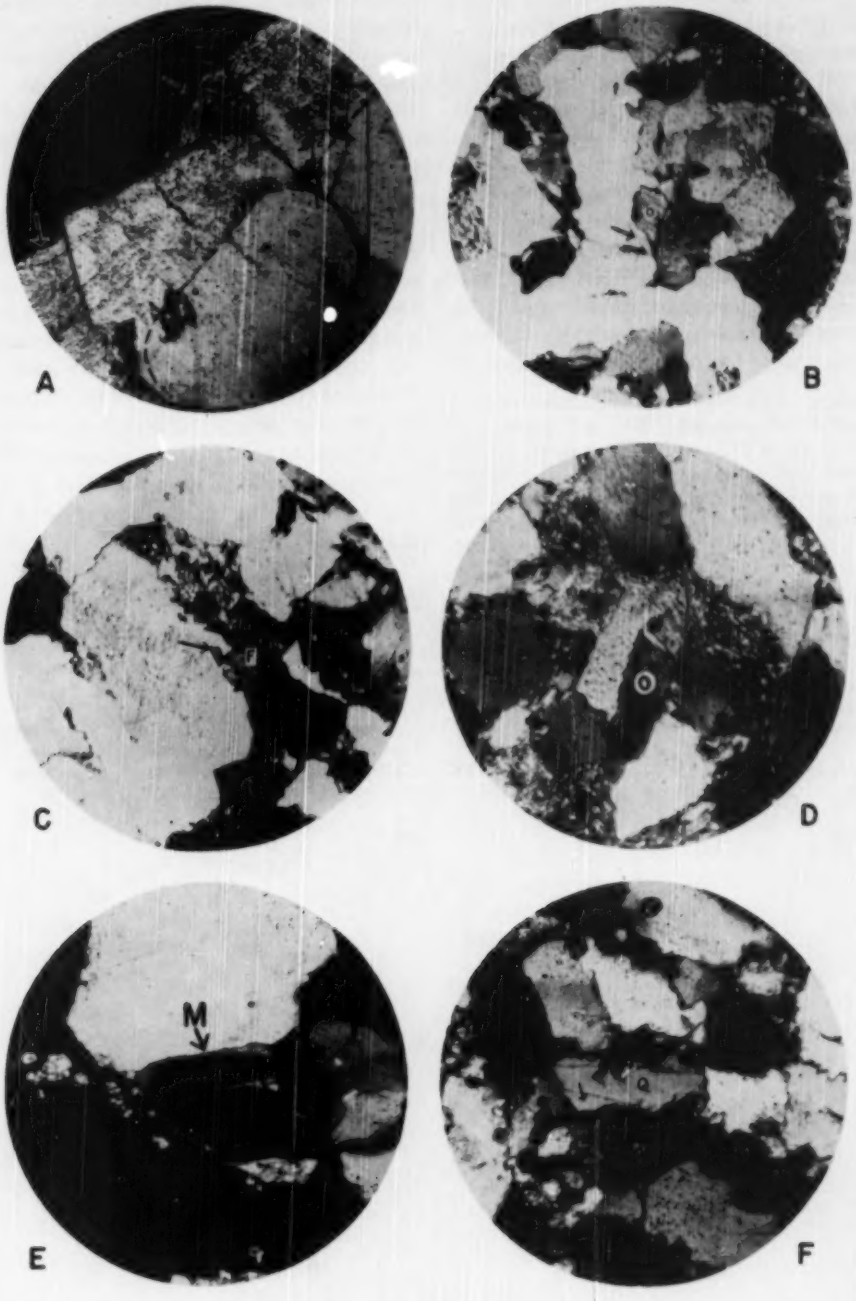
B, Big Injun sandstone. Detached fragment (*arrow*) from orthoclase grain (*O*), embedded in secondary quartz. Crossed nicols, ×100.

C, Big Injun sandstone. Detached fragment (*arrow*) from feldspar grain (*F*) has been engulfed by secondary quartz. Crossed nicols, ×100.

D, Big Injun sandstone. Crack in fractured orthoclase grain (*O*) filled with secondary quartz. Crossed nicols, ×120.

E, Oriskany sandstone. Fractured grain of microcline (*M*) cemented by secondary orthoclase (see also fig. 3). Crossed nicols, ×120.

F, Berea sandstone. Illustrates the mutual penetration of quartz grains, with conspicuous suturing along the contacts. Note that the boundary of the secondary enlargement (*arrow*) on quartz grain *Q* is not sutured, whereas the contact along the detrital portion is highly sutured. Crossed nicols, ×75.



Oriskany, Big Injun, and Berea sandstones

solution of the grains at the points of contact because the secondary growths are free of solution effects, although they are commonly in contact with other grains (pl. 3, *F*). If deposition of silica had begun at the same time as solution, the early growths between detrital grains which show considerable interpenetration could hardly have escaped some degree of solution. At one time solution of quartz was apparently favored by the chemical composition of the solutions present in the rock. With a later change in the composition of the solutions, the quartz ceased to be dissolved, and silica was then deposited in the open spaces. The solution of quartz is not simply related to depth of burial because sutured contacts are lacking in many of the deeper sediments and yet occur in some of the relatively shallow sediments.

In many of the calcareous sandstones the quartz grains are separated by a continuous matrix of clastic calcite. Silica for the secondary growths in these rocks could not have originated through pressure solution of the quartz grains.

Most of the calcite cement has probably resulted from the solution and reprecipitation of calcareous material originally present in the rocks. Not all the calcite was redistributed, however, because numerous oölites and calcareous shells are well preserved in many specimens.

ACKNOWLEDGMENTS.—The samples studied were largely from the collections of the West Virginia Geological Survey. The writer is indebted to Dr. John C. Ludlum for critical reading of the paper. Thanks are due Thomas E. Garnar, Jr., for assistance in taking the photomicrographs.

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PEDIMENTS AND PEDIMENT-FORMING PROCESSES NEAR HOUSE ROCK, ARIZONA[1]

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ABSTRACT

At the base of the East Kaibab monocline, 6 miles south of House Rock, Arizona, stand two levels of pediment remnants, cut largely in Moenkopi red shales and capped by boulders and gravels of Kaibab limestone. The pediments are produced primarily by lateral corrasion by master-streams, aided by rill-wash and gully erosion. Pediment-cutting has been interrupted by periods of aggradation in which thick protective gravels were spread upon the pediments.

INTRODUCTION

An important element in the Colorado plateaus in northern Arizona is the occurrence of small pediments and dissected pediment remnants in weak shale or marl formations at the foot of erosional escarpments and monoclinal flexures. This paper describes a particularly striking series of such pediment remnants and analyzes pediment-forming processes apparently operating at the present time.

The pediments lie at the topographic base of the East Kaibab monocline, approximately 6 miles south of House Rock (on U.S. Highway 89) and 12 miles east of Jacob Lake (fig. 1). The extreme westernmost part of the area treated in this paper lies within the Jacob Lake quadrangle (Coconino County), published by the United States Geological Survey in 1940, on a scale of 1:62,500.

A topographic map (fig. 2) was compiled by the writer from air photographs, with the aid of the Fairchild Stereocomparagraph. Field work and a series of timber-type maps, published in 1941 by the United States Forest Service for the North Kaibab Division of the Kaibab National Forest, provided control for the map. Contours in the western part of the map are taken from the Jacob Lake quadrangle.

Field research was done in the summer of 1946 under the supervision of Professor Arthur N. Strahler, of Columbia University, who critically read the manuscript.

TOPOGRAPHY AND GEOLOGY

The East Kaibab monocline forms the eastern margin of the Kaibab plateau, a high arch, 8,000–9,000 feet in elevation, bordered on the east, north, and west by lower plateaus and truncated on the south by the Grand Canyon of the Colorado River. The monocline is a double flexure, which joins the horizontal beds of the Marble Platform on the east with the near-flat strata of the Kaibab Plateau on the west (figs. 1 and 3). Vertical displacement is approximately 3,000 feet, but, because it is attained over a distance of about 10 miles, dips do not exceed 15°. The monocline and plateau surfaces now coincide approximately with the upper surface of the resistant Kaibab limestone, from which a great thickness of Triassic, Jurassic, and Cretaceous formations has been stripped.

Standing 2,000–3,000 feet above the

[1] Manuscript received June 7, 1948.

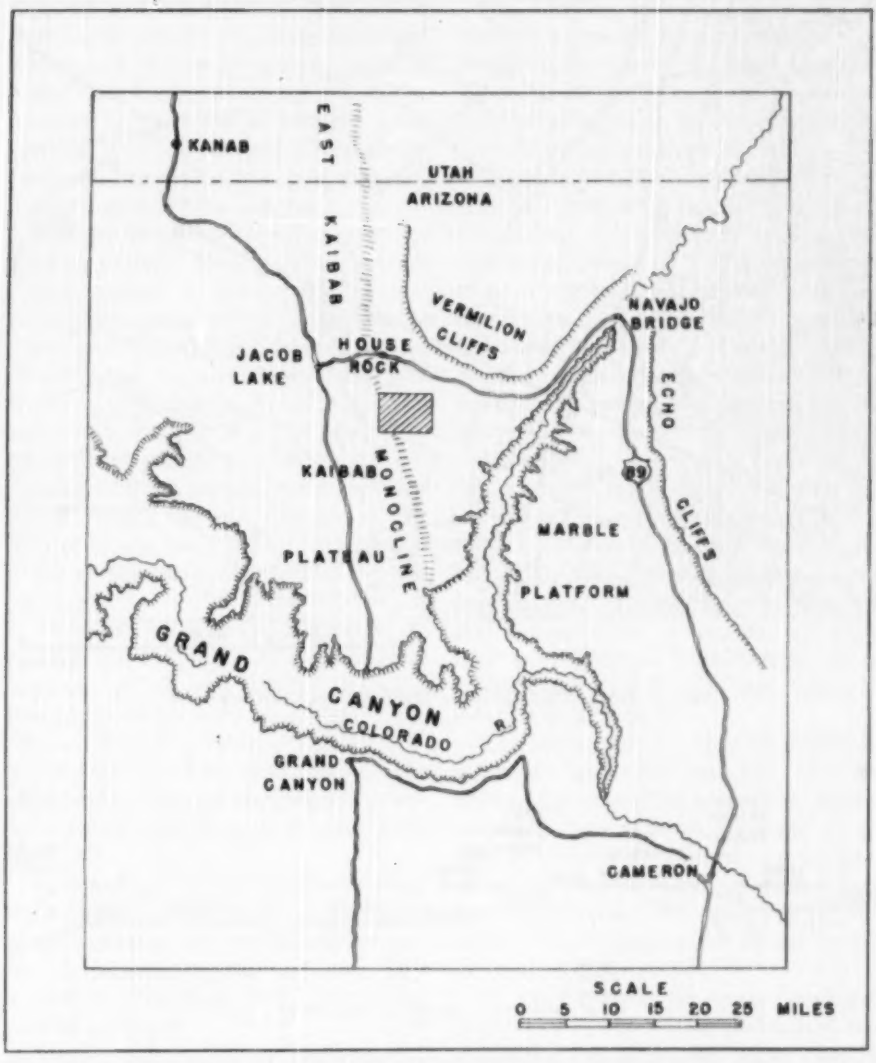

FIG. 1.—Index map of the Kaibab Plateau–Marble Platform area of northern Arizona. The location of the House Rock pediment remnants is indicated by the small shaded rectangle.

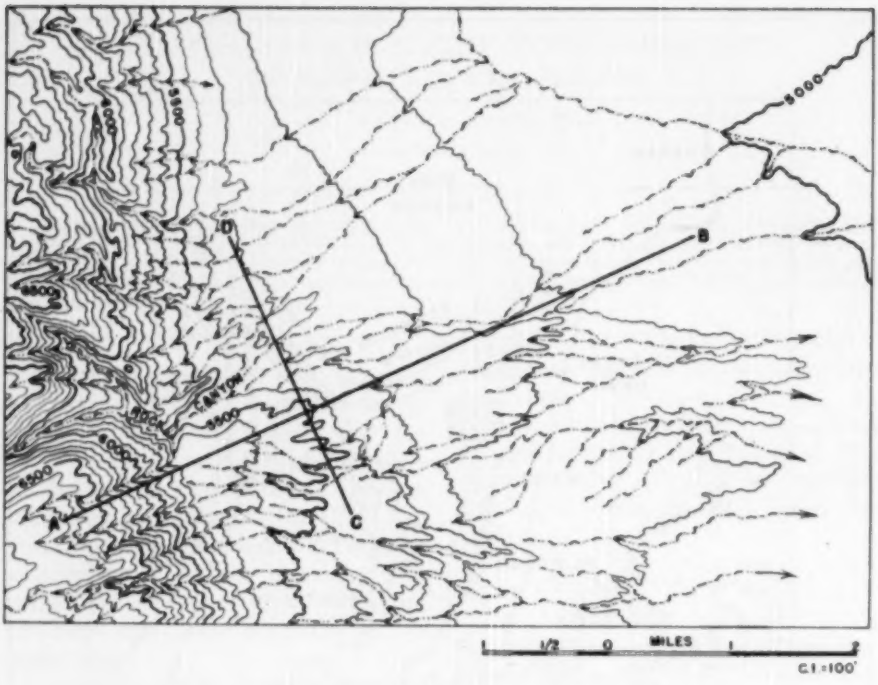

FIG. 2.—Topographic map of the House Rock pediment remnants

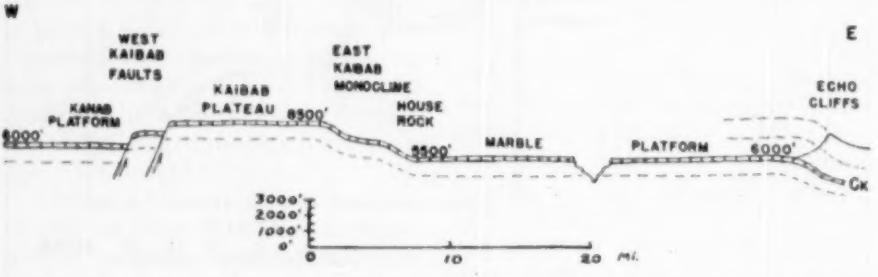

FIG. 3.—Cross section of the Kaibab Plateau–Marble Platform area. The section crosses the index map (fig. 1) from west to east, passing through the House Rock pediment area, indicated thereon by the small shaded rectangle.

surrounding country, the Kaibab Plateau receives abundant precipitation and supports a rich coniferous forest, intermixed with stands of quaking aspen and interrupted by grass-covered natural parks. On the other hand, the pediments, lying at an elevation of between 5,000 and 5,750 feet at the foot of the monocline, are in a semiarid climate, supporting only sparse grass and sage.

The gently rolling topography of the Kaibab Plateau gives way to a more rugged surface on the eastward monoclinal slope, owing to the incision of the drainage. Where the east-flowing streams cross the fold, canyons are cut to a depth of about 1,000 feet, as in Kane Canyon and South Fork of Rock Canyon. The topography abruptly changes at the mouths of these canyons to a low, dissected surface, sloping eastward to the floor of House Rock Valley, and is composed of the pediments treated in this paper.

There are no permanent streams, all runoff being accomplished in a relatively brief period following rainfall. In addition to the major streams coming off the plateau, a large number of smaller consequent streams have developed on the abandoned pediment surfaces but as yet have entrenched themselves very little (pl. 1, *A*).

Rills and gullies are numerous along the side slopes of the pediment remnants, which are being reduced as a lower surface is formed at their expense. This activity is treated in detail in another part of the paper.

GEOMORPHOLOGY

DESCRIPTION OF THE PEDIMENTS

Viewed from House Rock, the pediment remnants appear as flat-topped benches extending eastward from the foot of the East Kaibab monocline (pl. 1, *B*). There are two distinct remnant levels. The upper stands some 200 feet above the present stream-cut surface, or about 140 feet above the lower remnant. Figure 4 shows the areal extent and interrelation of these remnants with the present stream-cut surface.

Dipping beds of Moenkopi shale are perfectly truncated by the pediments. Locally, at the innermost edge of the pediments, even the hard Kaibab limestone layers are beveled by the pediment surface (fig. 5, *A*). The Moenkopi shales have been truncated along a plane whose profile, normal to the mountain face, parallels the gradients of streams flowing eastward from the flank of the monocline.

Noteworthy is a gravel capping, 85 feet thick, on the highest level. The top surface of the capping gravel exhibits a remarkable parallelism with the truncating pediment surface. The gravel is composed almost entirely of well-weathered Kaibab limestone fragments, up to 3 feet in diameter. These show chert nodules, silicified fossils, and irregular solution indentations.

The surface of the upper remnant is extremely well preserved and, near its apex at the base of the monocline, has an eastward slope of between 3° and 4°. It supports several shallow consequent streams, which have cut only a few feet into the gravels. The steep margins of both remnant benches are scored by innumerable small gullies.

At Rock Canyon the upper bench extends only 1¼ miles from the base of the monocline, whereas the lower bench reaches out a distance of 4½ miles.

The lower bench, unlike the upper, is overlain by a gravel capping, only 10 or 12 feet thick. Its surface is dissected by a much more extensive system of consequent streams. Caliche was noted as a

cementing material in the gravels of this surface.

RELATION OF STREAMS TO PEDIMENTS

The main streams are cutting laterally into the flanks of the lower bench. In those places where the passing streams lie at some distance from the foot of the bench, considerable erosion has been accomplished by rills and gullies. Locally, small knobs were isolated, 100–150 feet from the main mass.

Embayments of the lower pediment remnant, extending into the upper one, are prevalent (fig. 4), and in one such embayment a fine example of a laterally corrading stream was noted. Intergully spurs are truncated where the stream impinges upon the slopes of the pediment bench. Small fans are built up in the bed of the main stream by gullies whose gradients were steepened by lateral shifting of the main stream (fig. 6).

In this same embayment, farther upstream, undercut and oversteepened slopes are present on one side of the embayment, whereas a much more gentle slope, indented by numerous gullies ending in fans, is present on the opposite side (fig. 7). The activity of gullies and master-streams is also well illustrated near the mouth of Rock Canyon, where active undercutting has produced walls which in places stand almost vertical (fig. 8). Another example of undercutting and truncation of lateral gullies was seen at the point marked *x* in figure 9. Forty feet upstream, where the master-stream temporarily swings out from the valley wall, there were complete gullies and fans.

The present surface of denudation, on which the streams flow after emerging from canyons in the monocline, is covered with detrital material comparable with that of the lower pediment remnant. Boulders of Kaibab limestone more than 4 feet in diameter were found near the mouth of Rock Canyon.

The gradient of the master-stream and therefore of the pediment now being formed is $2\frac{1}{2}°$ near the apex, decreasing downstream to less than 1°. The dip of the truncated Moenkopi formation is a little more than 4°.

Where flat-floored valleys have been cut, the streams tend to lie close to one side or the other, with parallel tributaries occupying the opposite side of the valley. A transverse profile of such a valley has two channels and a faint convexity between. This double-channel form is common in arid regions, where the center of the wash has been choked with coarse debris by the master-stream.

The surface being carved by present streams is a new pediment in the process of formation. About 5 miles east of the monocline it is slightly trenched by streams, which, if they erode headward into the present surface, will produce an elevated bench similar to the present benches.

PRESERVATION OF PEDIMENT REMNANTS

The Moenkopi shale is extremely weak. If the pediment remnants had been unprotected, they would have been

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PLATE 1

A, Stereopair of the House Rock pediments, showing Rock Canyon, the base of the East Kaibab monocline, and the gravel-capped pediment remnants. North lies toward the left of the photographs. Use a lens stereoscope to obtain stereoscopic vision.

B, Ground panorama of the House Rock pediment remnants, showing two distinct levels, with present pediment in foreground. Photograph by A. N. Strahler.

A

B

House Rock pediment and pediment remnants

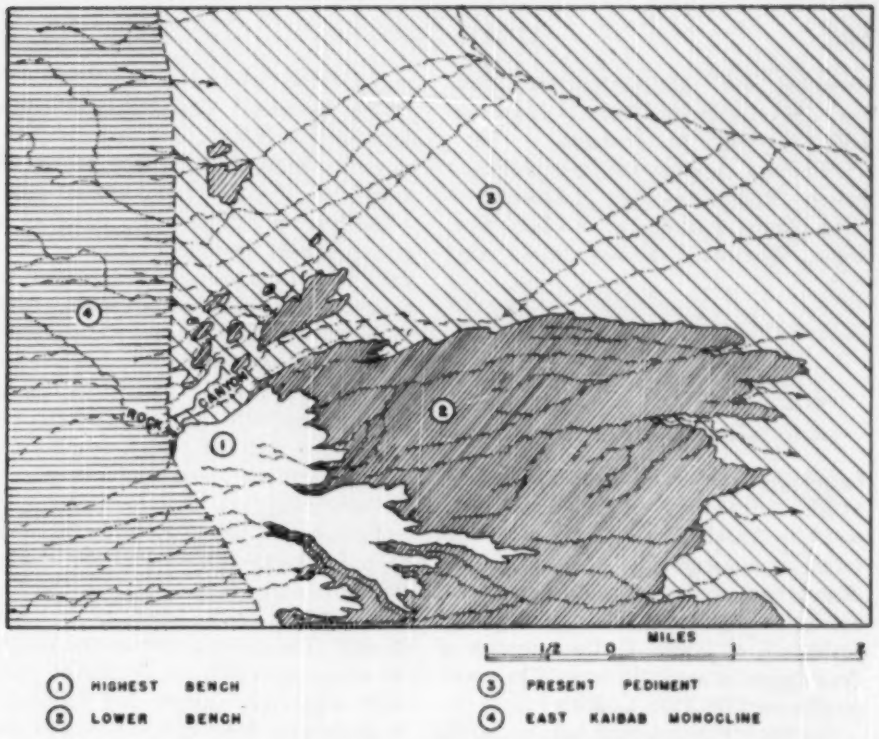

FIG. 4.—Map showing the extent of the House Rock pediment remnants. Surfaces *1*, *2*, and *3* on this map are well shown in sections *A* and *B*, figure 5.

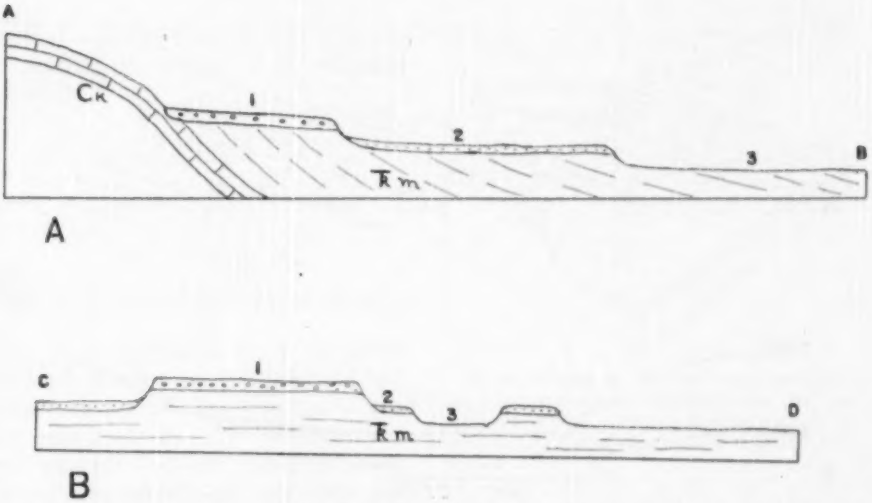

FIG. 5.—Diagrammatic cross sections of the House Rock pediment remnants. *A*, section along line *AB*, figure 2. *B*, section along line *CD*, figure 2. The horizontal scale of section *B* is almost twice that of section *A*. Extreme vertical exaggeration.

dissected much faster than they have been. Several factors seem to have contributed to their preservation.

Alluvium capping the two pediment benches and the modern pediment consists almost entirely of Kaibab limestone. Weathered Kaibab fossils were found over the entire area. The gravel, at least 8 feet thick on the present pediment level and thicker on the older surfaces, is a formidable obstacle to the destructive agents of weathering, sheet erosion, and gullying. The high degree of resistance of gravel to the agencies of denudation in semiarid regions has been emphasized by John L. Rich (1911).

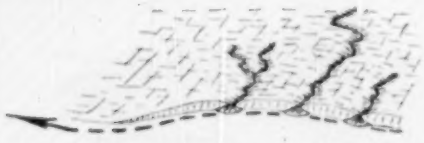

FIG. 6.—Sketch of small fans at gully mouths

On the lower pediment bench, caliche has formed a massive cemented zone in the capping gravels over the entire remnant surface. Small streams, consequent on the pediment slope, have thereby been prevented from incising their channels into the weak underlying Moenkopi shales.

Gullies, eating into the flank of a gravel-capped pediment remnant, are very active on the exposed Moenkopi shale; but where limestone detritus from the overlying gravel covers the shale the slope is effectively protected. Flatiron-like surfaces, armored by resistant limestone gravel talus, stand out from the base of the scarp by reason of gully enlargement in the weak shale deeper in the bench (fig. 10).

The detrital capping, either in place or in a reworked location at the base of the scarp, does not have much protective value against lateral corrasion by larger streams. The gravels increase the load to be removed, which an uncapped pediment would not supply, but resistance to erosion by flood flow is probably not great.

A stream immediately south of Rock

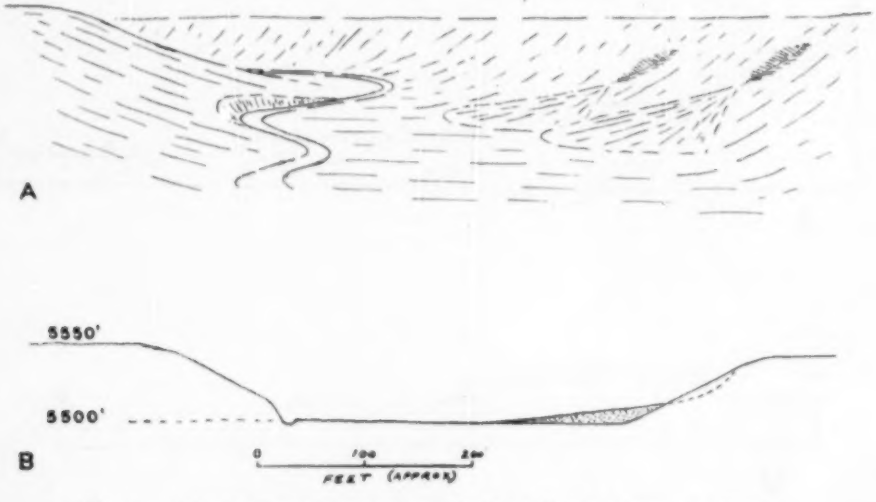

FIG. 7.—*A*, sketch of embayment in remnant; *B*, profile of embayment in remnant

Canyon turns north near the base of the monocline, at the Kaibab-Moenkopi contact, joining Rock Canyon at its mouth (fig. 2). The effect is to preserve the pediments to the east of this junction, because there now is one transecting stream and not two, as would otherwise be the case. This portion of the pediment remnant is now partially rock-defended by the entrenchment of Rock Canyon and its tributary into bedrock, 50–150 feet below the highest pediment remnant.

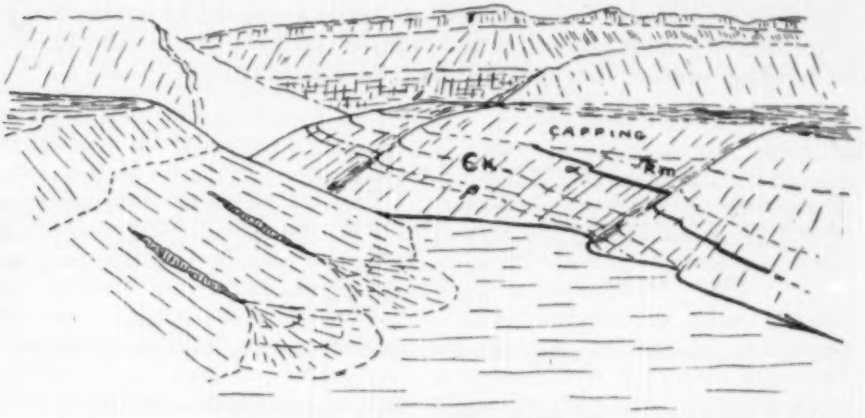

FIG. 8.—Sketch of the mouth of Rock Canyon

FIG. 9.—Sketch of undercutting and gullies

At the easternmost tip of the lower pediment bench a small monoclinal fold brings the Kaibab limestone up to the pediment level (fig. 11). Remnants extend eastward several hundred yards beyond this monocline, but they are much smaller and more poorly preserved than that part remaining on the west side. Doubtless the Kaibab limestone was much more effective in resisting lateral cutting than were the weak red shales of the Moenkopi.

Thus five factors seem to have contributed to the preservation of the former pediment surfaces in the House Rock area, namely, (1) a thick capping of resistant limestone gravels, ranging in

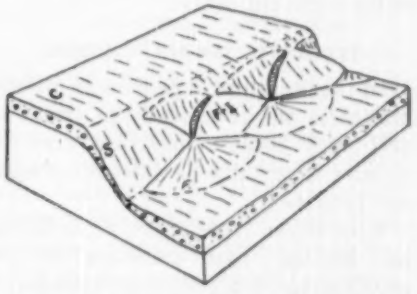

FIG. 10.—Sketch of "flatiron" forming in limestone talus between fan and gully systems. Features represented are *C*, pediment-capping gravels; *S*, slope cover; *F*, alluvial fans; and *F-I*, flatiron forms.

coarseness up to boulders several feet in diameter; (2) cementation of this capping with caliche; (3) limestone gravel veneer on the dissected slopes of the remnants, which protects pediment benches from excessive rill-wash and gullying at their edges; (4) coalescing of streams from the monoclinal slope before reaching the pediments, thus reducing the number of through-passing streams and hence reducing the zones of strong lateral stream corrasion; and (5) presence of a small monoclinal flexure, bringing resistant limestone to the surface 5 miles east of the main monocline, near the outer fringe of the pediment remnants, and thereby preventing easy lateral corrasion and undermining of the pediment bench.

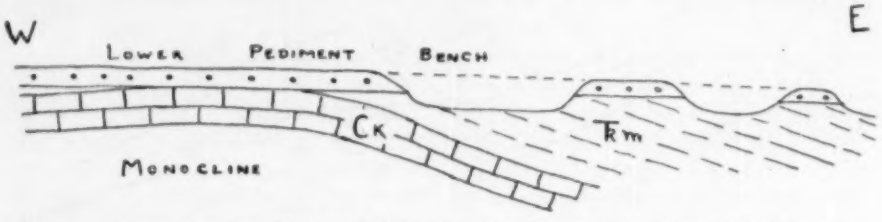

FIG. 11.—Cross section of easternmost tip of lower pediment remnant, showing monoclinal structure

PEDIMENT-FORMING PROCESSES

In the literature of pediments, several references are particularly pertinent to this study because they deal with the relative importance of lateral corrasion and rill-wash.

Kirk Bryan (1922, 1925, 1936; Bryan and McCann, 1936) considers that the principal agent in pediment formation is the ephemeral stream, which works by incision and lateral planation. Rainwash, rills, and weathering are, however, particularly effective in the later stages of the process. Retreat of mountain slopes is by weathering and rainwash, and the break in slope between mountain and pediment is apparently due to the increased efficiency of transport of streams over rainwash.

Douglas W. Johnson (1931, 1932*a*, *b*, *c*) ascribed pediments almost wholly to lateral corrasion by graded streams issuing from a mountain front. Laden with debris, the streams are incapable of much downward cutting but are able to cut laterally into the mountain base. Rock fans are formed by streams held at canyon mouths but free to sweep radially in the zone of lateral corrasion and impinge upon the mountain front on either side.

John L. Rich (1935) has stressed the importance of sheet-wash in the origin and evolution of rock fans and pediments along the Book Cliffs, Utah, under conditions somewhat like those at House Rock. He states that concentrated channel flow, although playing a part in the maintenance of these features, is not necessarily the instrument by which they are 'carved." Lateral planation of streams, though often contributing to pediment formation, is by no means a necessity.

R. P. Sharp (1940), in studying the Ruby–East Humboldt Range in northeastern Nevada, was fortunate in observing pediments obviously formed under several different sets of conditions. He concluded that the formative agents

were planation, rill-wash, weathering, and rainwash and that such factors as geology, topography, and climate served as controls determining which of the above agents should be most active in a given area. He noted that a combination of permanent streams and soft rocks is most favorable for lateral planation, whereas intermittent streams, hard rocks, and low mountain masses increase the relative importance of weathering, rill-wash, and rainwash.

Sharp's analysis is of particular interest in the present study because it deals with pediments formed on soft materials, somewhat analogous to the pediments of the House Rock area.

Two pediment-forming processes appear to be predominant in the destruction of previous pediments and in the formation of a new pediment along the base of the East Kaibab monocline. They are (1) lateral corrasion and (2) rill-wash and gullying. A very definite interplay exists between these two processes in the development of the House Rock pediments. The following appears to be the history in this area:

As a monocline is first attacked by erosive agents, downcutting by streams is of primary importance. When profiles of equilibrium have been established by the major streams, lateral corrasion assumes a dominant role.

Undercutting takes place first on one side of the stream valley, then on the other, as the braided streams shift their courses. While undercutting is taking place on one side, gullies on that side feed their detrital material directly to the channel of the master-stream. Across the valley, where no through-flowing stream operates, small fans are built up at the mouths of the small tributary gullies. Here retreat of the valley wall produces a very irregular and crenulate scarp. Eventually, the master-stream swings back to this side, removing the alluvium accumulated at the mouths of the gullies and cutting farther back to replace the gullied slope by a smooth, steep slope. At this time the gullying and fan-building process is repeated on the newly abandoned scarp across the valley. Here the gullies, which formerly dumped their material directly into the passing stream, now build up a series of fans and continue to effect scarp retreat. Fans thus built up are reduced by rainwash, but removal does not keep pace with accumulation.

It was commonly noted that where the main stream is flowing along one side of the valley, a subparallel tributary has formed along the opposite side. In these cases the simple relations described above are altered, with lateral corrasion active on both sides.

Where undercutting occurs, gullying and rill-wash serve as close contributive partners. Where no stream is present, gullies and rills operate quite effectively on their own.

Rich (1935) maintains that lateral corrasion is not necessary for the formation of pediments but that streams exert merely a controlling effect on the level of denudation. It is the writer's conclusion not only that streams are important as grade controls but that they are equally important as active pediment-forming agents. The pediments of the House Rock area are carved mainly in extremely weak shales, with only local truncation of resistant limestone at the base of the monocline. Lateral corrasion undoubtedly has played a major role and probably would have been even more effective if the streams had been permanent and not ephemeral.

R. P. Sharp's conclusion that lateral planation is especially effective in areas

underlain by soft rock is well borne out in this area.

CLIMATIC HISTORY

Why were the two pediment surfaces of former times dissected, and why do they both have such a thick overlying coat of gravel? It does not follow from our present understanding of pediments that they should have more than a thin veneer of alluvial material.

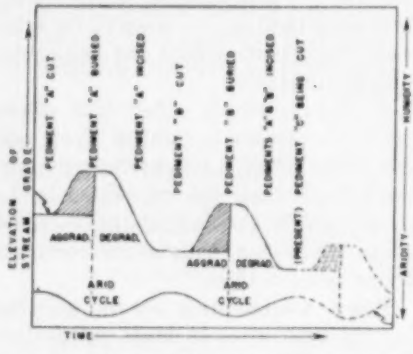

FIG. 12.—Diagram to illustrate the hypothetical relationship of climatic fluctuation to aggradation, degradation, and pediment-cutting near House Rock. Flat "humps" and "valleys" in grade curve indicate graded conditions established after each period of aggradation and degradation. Lower line shows climate cycles.

The streams responsible for these pediments are assumed to have undergone successive stages of (*a*) pediment-cutting and stability, (*b*) aggradation, and (*c*) downcutting to a lower level of stability in which a new pediment surface was formed.

Two hypotheses might be proposed for the sequence of events, namely, (1) alternate fall and rise in base level and (2) climatic changes, such as to produce a general regional denudation between two episodes of fan aggradation.

On the basis of field examination the second possibility seems the more likely. Although the Marble Platform consists of almost horizontal strata, some of which are resistant enough temporarily to avert downcutting of the east-flowing streams, these could serve only to check degradation and cannot explain two periods of aggradation.

It is therefore probable in the House Rock area that the thick gravel cappings were deposited during more arid periods, whereas stream entrenchment, re-establishment of grades at lower levels, and the production of new pediments were related to periods of greater rainfall (fig. 12).

At least one cycle of stream aggradation has been confirmed by A. N. Strahler (1940). Along the Vermilion Cliffs, bordering the Marble Platform on the north and but a few miles from the House Rock pediment benches, some of the great slump blocks lying at the cliff base are truncated by a bench some 180 feet above the present pediment slope. Another bench, farther east, is 300 feet above the present pediment. Strahler explained these rock benches as partial pediments produced by lateral planation in a cycle of aggradation which followed landsliding. Alluvium was built up to a height approximating the upper part of the blocks. Otherwise it is difficult to understand how the slump blocks could have been planed off and a bench produced.

Although Strahler supposed that the landsliding provided great masses of loose debris which was readily washed into the stream, thereby causing aggradation, it seems more reasonable that the slides occurred in a more humid cycle, whereas aggradation followed in a more arid cycle somewhat later. The massive capping of gravels on the highest pediment bench south of House Rock may have been laid down in the same cycle of aggradation as that in which the slump blocks were partly buried and beveled.

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GEOLOGICAL NOTES

NOTES ON ICE-FOOT DEVELOPMENT, NENY FJORD GRAHAM LAND, ANTARCTICA[1]

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INTRODUCTION

Wright and Priestley (1922, p. 581), in their classic work on Antarctic glaciology, suggest the term "icefoot" for the ice formation which joins the land and sea ice between high- and low-water marks. This is a glaciological feature of considerable geological importance, since, while it is fast to the beach formation, it affords complete protection against erosion. When it disintegrates, however, it becomes a powerful transportation agent, as masses of beach material are rafted away on the undersurface of the ice. Wright and Priestley classify ice-foot formations as follows: (1) the tidal platform ice foot, formed by tide action between high- and low-water marks; (2) the storm ice foot, built up above high-water mark by spray from breaking waves; (3) the drift ice foot, fabricated from drift and consolidated by sea water which surges through the tide cracks; (4) the pressure ice foot, formed by overriding slabs of sea ice emplaced by an on-shore movement of the sea ice; and (5) the stranded-floe ice foot, incorporating beached "bergy bits."

Two additional types of ice foot are described below: the "false ice foot" and the "wash-and-strain" ice foot.

A "FALSE ICE FOOT"

When Stonington Island, Neny Fjord, Marguerite Bay, was occupied as the site of Base E, stores were unloaded on the shingle beach below Trepassey House (Base E hut). This beach lies between high- and low-water marks and is backed by a shingle step, which varies from 5 to 8 feet in height. During the unloading operations, there was a sharp rise in the day temperatures, and stores, dumped on the edge of the step, had to be moved back because of the melting of a seam of ice embedded in the step. This ice seam led the writer to speculate on its probable mode of origin. Later he was able to see a similar seam of ice formed and embedded in the shingle, as described below.

On April 12 and 13, 1946, there was a heavy fall of snow, during which there fell 15.7 mm. *of precipitation*, or 28 per cent of the total for the month. Following this snowfall, the maximum day temperatures were well above the freezing point, but, for the major portion of the 24 hours, the temperature was below the freezing point. During the warmer spells, meltwater flushed through the snow. As the temperature fell each afternoon, the drainage of water from the lower edge of the snow, which was at the edge of the shingle step, became very torpid. As freezing occurred, it formed an ice cornice on the face of the step (fig. 1, *A*).

The structures in the ice composing this cornice closely resembled those of sinter terraces, as small-scale flow sheets, whorls, rims, and curtain stalagmites were common on the forward edge. When the supply of meltwater ceased, about April 21, ablation smoothed the exposed faces, so that the shingle step was protected by an ice formation, the base of which lay at high-water mark. It has been termed a "false ice foot"

[1] These notes are abstracted from the ice diary kept by the writer while serving with the Falkland Islands Dependencies Survey. They are published with the permission of H.M. Under Secretary of State for the Colonies. Manuscript received February 17, 1950.

because a true ice foot has its base at or below low-water mark.

The "false ice foot" persisted until May 5, when an east-southeast wind, varying between 24 and 30 m.p.h., raised a heavy sea. This broke up most of the ice in the center of the beach, as heavy waves dashed above high-water mark. Considerable portions of the ice, however, remained firmly anchored to the beach at the ends of the small bay. Where the sea did not destroy the ice formation, it was covered by a layer of storm beach material, mostly of cobble grade. The amount of material cast up from below high-water mark was considerable, as the ice was covered to a depth of a foot or more. Melting of the ice back to the shingle step left a seam of ice in the shingle (fig. 1, *B*).

In this sequence of events the writer saw the explanation of the feature which proved so troublesome during the unloading of the stores.

A "WASH-AND-STRAIN" ICE FOOT

The formation of this ice foot occurred during a period when *swell* and not *sea* was the principal form of disturbance of the water. As this must be a comparatively rare happening in the Antarctic, the formation of the ice foot during these conditions is of special interest.

From April 22, 1946, onward, pebbles on the shore washed by waves developed thin coatings of ice, which, for convenience, it is proposed to term "ice casts" (fig. 2, *A*). These ice casts were not at first permanent, as they melted under a slight rise in temperature and any large wave tended to break them off the parent-pebble. Under favorable conditions they coalesced to form low mounds of rather porous ice (fig. 2, *B*). From the first, however, it was evident that the mechanical factor due to the rolling of the pebbles was more important in their destruction than were temperature effects.

Before the ice casts became permanent, bottom ice appeared below low-water mark on May 20 (fig. 2, *C*). This bottom ice at first was in the form of a cloud of spicular crystals, which formed a layer in shallow water, extending only some yards below low-water mark. The individual crystals were only loosely held together. On being stirred up by wading, they floated up in dense clouds. Settlement was apparently rapid, but the specific gravity/temperature relations of ice are such that the apparent sinking of the ice in water, instead of its flotation, calls for some special explanation. The surface-water temperature on successive days was 28°.8, 28°.6, 28°.8, and 28°.9 F.;

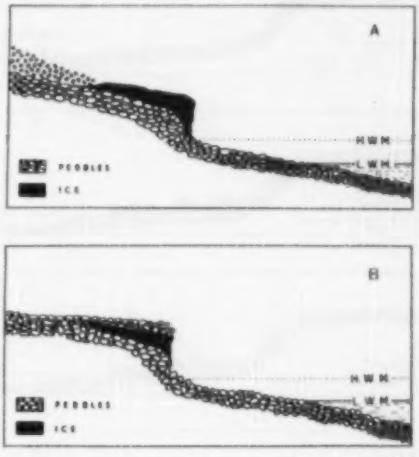

FIG. 1.—Sketch of *A*, the false ice foot, and *B*, the seam of ice after partial destruction and acquisition of cobble cover.

that is to say, the temperature was just above the freezing point of water, with a salinity of 35 parts per thousand. This temperature is also the point of intersection of the curve of temperature of *maximum density with increasing salinity* and the curve of the depression of *freezing point with increasing salinity*. Any further lowering of the temperature of the water *without freezing* will result in an increase and not a decrease in density, irrespective of the salinity. The spicular ice must therefore have been forming in a layer of water below and colder than the surface layer. As the ice spicules rose, they melted rapidly at the junction between the two layers. Those churned up were carried beyond this boundary and, as they

melted, produced the illusion of rapid settling.

On May 21 the ice casts became permanent, and spongy, coalesced lumps, which were reminiscent of some types of coral formations, had formed (fig. 2, *D*). By May 25 the ice spicules lay like a heavy slush on the surface of the water. This had the effect of damping the *swell* to a very considerable extent. As the swell washed over the ice casts and coalesced lumps, part of this heavy load was trapped in hollows while the water strained out. By May 27 the ice foot was built up to high-water mark (fig. 2, *E*). This process was continued at high tide by the surge of swell breaking against the ice foot, so that by June 1 the platform was about a foot above high-water mark (fig. 2, *F*). From June 2 to June 4 there was a heavy fall of snow. By June 7 the sea had frozen and the ice foot had the appearance shown in figure 2, *G*, when the tide cracks had formed and the profile was rounded off by snowfall and drift. In its final form the ice foot was thus a combination of a "wash-and-strain" and a drift ice foot, as described by Wright and Priestley.

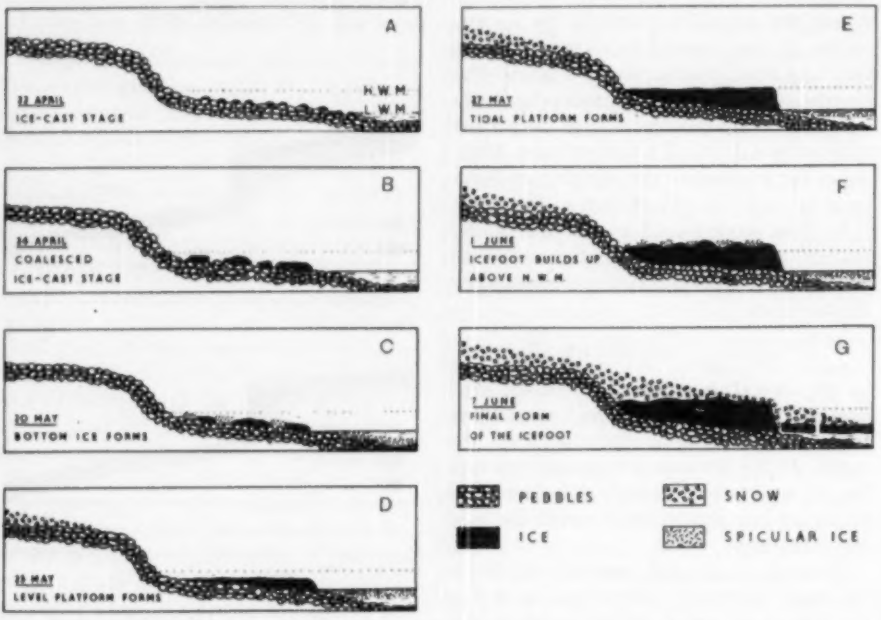

FIG. 2.—Sketch of stages in the formation of ice foot that is a combination of a "wash-and-strain" and a drift ice foot.

OTHER TYPES OBSERVED

Two other forms of ice foot described by these authors were observed forming at the same time as the "wash-and-strain" type. These are the storm ice foot and the stranded-floe ice foot.

The storm ice foot was observed only in a minor form in Neny Fjord. As stated above, *swell* and not *sea* was experienced during the freezing of the sea. The same swell which formed the "wash-and-strain" ice foot on the shelving beach broke against rocky prominences jutting out into the sea. The spicular ice crystals froze to the rocks and built up a small storm ice foot. On the shore of the narrow bay between Stonington

Island and the front of the piedmont glacier to the east, stranded "bergy bits" persisted through the summer. The ice foot here developed in the same manner as that described by Wright and Priestley for their stranded-floe type of ice foot.

Thus four types of ice-foot formation were observed. Three of these—stranded-floe, storm, and drift ice foot—have been previously recorded. The fourth, "wash-and-strain" ice-foot formation, is a specialized type of tidal platform ice foot originating through a mechanism not previously described. It is essentially the product of steadily falling sea temperatures and seas in which *swell* is the only disturbing component, and it requires a shelving beach for its formation.

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DISCUSSION

MICROSTYLOLITES IN PRE-CAMBRIAN QUARTZITE: A DISCUSSION[1]

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Smith College

Microstylolites in pre-Cambrian quartzite have been described by Conybeare (1949), who attributes them to solution of the rock along partings, accompanied by the concentration of residual specularite along the surfaces of the stylolites. However, Conybeare's descriptions and illustrations show that the stylolites antedate the consolidation of the sediments. They are, therefore, primary rather than secondary.

Conybeare's plate 1, *A*, shows that the quartzite is cross-bedded, a fact which is not mentioned by him. The foliation above the stylolite seam makes an angle of 12° with that below. The elongation of the quartz grains follows the direction of the foliation in each part. If the foliation were the result of pressure alone, it is difficult to see how its direction could vary so greatly in such a fine-grained rock. Although the pressure that was exerted upon the rock during recrystallization was undoubtedly important, it appears to have been less effective in the arrangement of materials than were the currents at the time of deposition.

High stresses and moderate recrystallization do not always destroy stylolites. Ptygmatic stylolite seams occur in the Tennessee "marble" (Shaub, 1949, fig. 2, p. 33). The sharpness of the interpenetrating parts in this case has been somewhat reduced, but the stylolite seam certainly has not been destroyed. The microstylolite seam illustrated by Conybeare also lacks the sharpness usually shown by undisturbed seams. The quartzite is so fine-grained that recrystallization has not seriously affected the configuration of the very small seam.

On page 84 Conybeare states that "all the quartz-filled fractures cut specularite stringers. Furthermore, the fracture illustrated in plate 1 is a minute fault, as indicated by the displacement of the band of coarser quartz beneath the stylolite."

I accept the interpretation that there has been some displacement of the band of coarse quartz beneath the stylolite seam, but I note that the part of the seam to the right of the fracture has likewise been carried up along with the "band of coarser quartz beneath the stylolite" seam without breaking the seam. I note, too, that the specularite stringers above the stylolite seam are much less regular than those below the layer of coarse quartz. In the lower third of the illustration no discernible displacement of the specularite stringers on the opposite sides of the fracture is apparent. The writer doubts that such *differential* displacement can occur in a quartzite. Therefore, the fracturing and displacement occurred before the material was consolidated (Shaub, 1949, fig. 3, p. 34).

Both Conybeare's illustrations also show another important feature not mentioned by him. Under crossed nicols, the elongated quartz grains appear practically continuous across the walls of the fracture. Therefore, the material within the clear area of Conybeare's plate 1, *A*, cannot be called a "fracture filling" in the accepted sense because there is no recognizable *filling* in the clear area. It is almost impossible to see any fracturing "between crossed nicols." If a fracture of the width shown in plate 1, *A*, and also indicated in Conybeare's diagrammatic sketch, figure 1, had occurred in a quartzite and the fracture had been filled with quartz, the structure of the filling would consist first of a thin band or skin of quartz, followed by a band or bands of quartz, and in each band the quartz grains, or poorly developed crystals, would be approximately normal to the wall and increase in size toward the center of the vein (Spurr, 1923, vol. 2, p. 677; Shaub, 1934, p. 39).

Conybeare (p. 84) states that "the stylolites were not all formed at the same time, as several of the quartz-filled fractures cut stylolites, although they are themselves cut by other stylolites," and that "where stylolites obliquely cut quartz-filled fractures, there is apparent dis-

[1] Manuscript received February 22, 1950.

placement of the fractures. This apparent displacement is not considered due to movement but to the effect of solution along the cross-cutting stylolites (fig. 1)." Apparently there was a period of fracturing between the two periods of stylolite formation. One may inquire, therefore, if the stylolites were formed by solution, why did not stylolites form along some of the cross-fractures during the later period of stylolite formation? The relations of the fractures and stylolite seams described by Conybeare, together with the differential displacements and continuity of the elongated quartz grains across the fractures, can be more logically explained on the basis of a primary origin of the stylolites and plastic adjustment before consolidation.

Many of the early fractures that form when sediments become firm enough to permit fracturing are undoubtedly rather weak, and consequently one would expect them to be narrow and relatively short. One would also expect them to end abruptly upon encountering some discontinuity, such as a previous fracture, a clay seam, or any definite parting. This phenomenon is a common one. Weak fractures through mineral grains commonly terminate at their boundaries, especially if the interstitial space contains softer material. It would therefore not be surprising to find that primary microstylolite seams may or may not be cut by the early fractures. This would depend entirely upon the strength of the small fractures.

If the material were under stresses which contained torsional components, one would expect the fractures to appear in a more or less echelon arrangement, and the weaker ones would end at the seam. Such fractures would appear to be offset. If it were not for the seam, against which the fractures end, the latter would overlap, as is the usual arrangement of echelon fractures.

In order that the offset of a fracture along a stylolite seam may be a measure of the amount of material removed by solution, it must be assumed (1) that the fracture is older than the stylolite seam, (2) that the fracture was originally straight and continuous, (3) that there was no displacement of the fracture along the plane of the seam, (4) that solution of the quartz actually occurred, and (5) that the specularite was insoluble. It is necessary, of course, to have the specularite retained and unaltered to form the seam parting. If the above assumptions are valid, then Conybeare's deductions as to the *amount* of quartz removed are correct. All this, however, *does not prove that any quartz has actually been removed by solution*, which is the crucial point of the theory of the secondary origin of stylolites.

The natural history of the stylolite in question is simple and straightforward. The history is as follows: (1) Deposition of the sediment, consisting of the materials now present in the quartzite plus associated water and possibly small amounts of adsorbed gases, took place. The materials were cross-bedded as they were deposited. They were very fine-grained and consisted essentially of quartz particles together with colloidal silica and iron oxides. Partings, now the stylolite seams, were slightly heavier and were more or less continuous bands of iron compounds and probably some admixed clay. (2) Sometime during the compaction and dewatering of the sediment and before consolidation and much reorganization of the material had occurred, the microstylolite seams were formed by volume contraction and differential pressure resulting chiefly from the loss of water. (3) When the material was firm enough to transmit light stresses, the so-called "fractures" were formed. They occur in various attitudes with respect to the already present stylolite seams. The fractures may, if of sufficient strength, cross the seams, or they may stop at the seam, and on the opposite side a new fracture may occur which is more likely to occupy an offset or echelon position than to meet the opposite fracture squarely and coplanar. (4) Small differential stresses in the unconsolidated sediment would be released or equalized by local plastic movement of the materials.

After the fractures were formed, colloidal silica moved gradually into the fracture zones and supplied the material to fill the "fracture" around the elongated quartz grains projecting from the walls. Disarrangement of the quartz grains occurred primarily along the fracture at the places where the quartz band and stylolite seam were displaced (Conybeare's pl. 1, *A*).

Absence of iron in the fracture zone shows that *the iron was already fixed in position* and was not so free to move into the fracture zone as was the silica. For the same reason, one is certain that the iron was a primary constituent of the sediment and was not introduced. Continued recrystallization brought the sediment to its present condition without severely altering the initial structures or those dating from the time of consolidation.

The microstylolites described by Conybeare are therefore primary rather than secondary. The features possessed by the microstylolites and the environment in which they occur can be logically accounted for by the normal processes which are active during the period of sedimentation, compaction, and consolidation. The secondary, solution theory involves too many improbable assumptions to be an acceptable account of the origin of microstylolites in quartzite.

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MICROSTYLOLITES IN PRE-CAMBRIAN QUARTZITE: A REPLY[1]

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In the January, 1949, issue of this *Journal* the writer published a description of microstylolites in pre-Cambrian quartzite. These were shown to be of secondary origin. The best explanation of their development is given by the solution-pressure theory. Elsewhere in the current issue certain arguments have been advanced by M. B. Shaub to show that these stylolites are not secondary but primary and were formed during compaction of the sediment. The writer welcomes this opportunity to reply to these arguments and to present further evidence supporting the solution-pressure theory.

The field relationships of this quartzite are such that the preservation of primary sedimentary features can hardly be expected. The quartzite is markedly schistose, as indicated by the orthorhombic symmetry of its quartz fabric (fig. 1), and occurs as a lenticular band a few feet wide and several hundred feet long within hornblende schist. The country rocks are granites, gneisses, and schists; granitization and mylonization, as described by Conybeare and Campbell (1949), are widespread. The amount of internal deformation which these rocks have undergone, as indicated by boudinage structure and lenticularity of the foliation, would have in large part, if not entirely, destroyed any primary sedimentary features, such as cross-bedding. Yet Shaub states that the quartzite in question (Conybeare, 1949, pl. 1, *A*) is cross-bedded and that the foliation above the stylolite seam makes an angle of 12° with that below. He is correct in this observation. However, the fact that the foliation *appears* to be cross-bedding does not justify the conclusion that it *is*. The angle between the foliation above and below the stylolite (Conybeare, 1949, pl. 1, *A*) can be more logically explained by assuming some variation in the amount of quartz dissolved along the stylolite seam (fig. 1). In agreement with this interpretation is the 12° angle between the portions of the quartz-filled fracture above and below the stylolite (fig. 1; and Conybeare, 1949, pl. 1, *A*).

In his previous paper the writer shows that a quartz-filled fracture cuts the foliation, indicated by specularite stringers, and is itself cut by a stylolite. Studies by Allan and Cameron (1922), Christie and Kesten (1949), and the writer indicate that hematite is abundant in the Goldfields area of Saskatchewan and that it was introduced during a period of widespread crushing and shearing. For this reason the writer infers that the hematite stringers in the quartzite were formed during a period of deformation when, as is evident from the quartz fabric (fig. 1), the quartzite was intensely sheared. The quartz-filled fracture, which is itself cut by the stylolite, could have developed only after the quartzite became schistose.

Shaub accepts the interpretation that there has been some displacement along this fracture but is of the opinion that movement took place prior to consolidation of the sediments. His evidence for this assumption is not acceptable. He states that differential displacement has occurred because he can see no displacement of the

[1] Manuscript received March 27, 1950.

specularite stringers on the lower third of the photograph (Conybeare, 1949, pl. 1, *A*), although displacement is evident in the center. Examination of the lower part of this photograph shows that there is no feature by which one specularite stringer can be distinguished from another and that it is therefore impossible, without any marker, to determine whether there has been any displacement. Shaub doubts that differential displacement can take place in quartzite, and he concludes that the fracturing and displacement antedate consolidation. The writer maintains that, even if it were possible to say with certainty that the photograph shows no displacement, all that can be seen in the plane of the photograph is the *apparent* displacement. Shaub does not appear to take into account the possibility of rotational slip along the fracture. Depending upon the position of a plane of view (the photograph) with respect to the displaced foliae, the apparent displacement of an individual folia would vary considerably. Shaub's argument that fracturing and displacement must have occurred before consolidation is therefore not valid.

It is pointed out by Shaub that the elongated quartz grains appear practically continuous across the walls of the fracture (Conybeare, 1949, pl. 1, *A*) and that the material cannot therefore be called a "fracture filling." In this observation he is correct; the quartz grains in the fracture show optical continuity with the grains in the walls of the fracture. However, as the writer has often observed this to be a feature of microfractures in gneiss, it cannot be explained as the result of compaction of sediments, as Shaub suggests.

Elsewhere in this issue Shaub states, "Partings, now the stylolite seams, were slightly heavier and more or less continuous bands of iron compounds and probably some admixed clay." It is evident that he views such partings as having been parallel or subparallel to the bedding prior to compaction and consolidation of the sediment. But the writer contends that stylolites in quartzite may cut the bedding at any angle. Examination of a quartzite from the pre-Cambrian rocks of the Kenora district, Ontario, shows stylolite seams cutting the foliation of a sheared quartzite at right angles. Megascopically and microscopically it is similar to the quartzite described by Conybeare (1949). If it is assumed that the foliation represents bedding, then Shaub's argument that stylolite seams develop subparallel to the bedding during compaction is disproved. If, on the other hand, the foliation is at right angles to the bedding, how would it have been possible to obliterate every trace of bedding and retain the stylolite? Microscopic examination of the quartzite shows that the foliation was produced by intense shearing or mylonization, and megascopic examination shows that the stylolites are younger than the foliation.

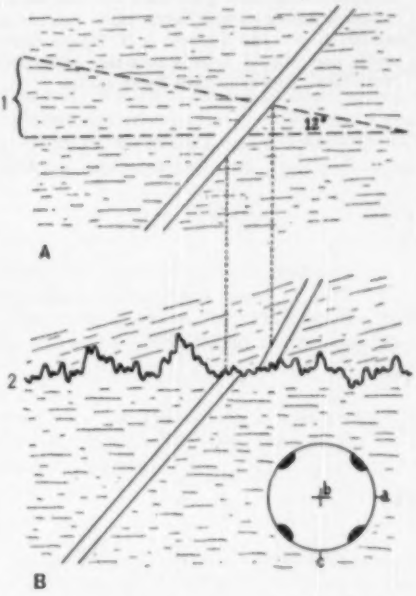

FIG. 1.—*A*, before solution, showing zone to be dissolved (*1*). *B*, After solution, showing displacement of foliation, resembling cross-bedding, caused by solution of a wedge-shaped portion of quartzite during formation of the stylolite (*2*). Note the apparent displacement of the quartz-filled fracture. A generalized diagram (*lower right*) shows the orthorhombic symmetry of the quartz fabric and the relationships of the tectonic axes, *a*, *b*, and *c*, to the foliation. The *a*- and *b*-axes lie parallel to the plane of foliation.

In conclusion, the writer would like to say that the question of origin of any particular stylolite should not be considered as a prima facie case based on previous interpretations. Further consideration may lead to the recognition of more than one type of stylolite and to a

sounder point of view on the fundamental problem of origin. As stated previously (Conybeare, 1949, p. 83), "The purport of this paper is not to suggest that *all* stylolites are of secondary origin but to demonstrate that in this instance the origin could not have been primary."

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REVIEW AND DISCUSSION[1]

Physical Principles of Oil Production. By MORRIS MUSKAT. New York: McGraw-Hill Book Co., Inc., 1949. Pp. xv+922. $15.00.

This book, issued under the auspices of McGraw-Hill's "International Series in Pure and Applied Physics," is in part a revision and in part an extension of the author's earlier book, *The Flow of Homogeneous Fluids through Porous Media*, published in 1937. Whereas the earlier book was restricted to homogeneous fluids, the present volume has been extended to include the flow of multiphase fluids (oil, gas, and water) also.

As to its contents, chapters i–iii are devoted to the physical properties of petroleum fluids and to pertinent properties of reservoir rocks; chapters iv–vi present the theory of the flow of single-phase fluids through porous solids; chapters vii–xi deal with multiphase flow problems; and the concluding chapters (xii–xiv) comprise such miscellaneous topics as secondary recovery, optimum well spacing, and related problems. In addition, some six to eight hundred citations of published literature have been made.

Like its predecessor, this book contains an enormous amount of otherwise widely dispersed information on nearly every important aspect of petroleum exploitation. Its avowed purpose, however, is the establishment of "those physical principles controlling the behavior of oil fields and their implications when applied under conditions broadly simulating those which may obtain in oil-producing reservoirs occurring in nature." Accordingly, the book is to be appraised principally on the degree of its success in achieving this objective. Since the fundamental relation involved in the flow of fluids through porous rocks is that known as "Darcy's law," a brief historical account of this relation will be useful as a basis for judgment in considering the treatment that has been employed.

In 1856 Henry Darcy studied the flow of water through filter sands. Using a vertical cylinder containing a sand pack of cross-sectional area A and thickness L, he observed that the volume of water, Q, flowing downward through this sand in unit time was given by

$$Q = -KA\frac{h_2 - h_1}{L}, \qquad (1)$$

where h_1 and h_2 are the heights above a standard datum of the water in input and output manometers, respectively, and K is a constant of proportionality. Expressing this differentially, the flow per unit area and unit time is given by

$$v = -K\frac{dh}{dL}. \qquad (2)$$

Darcy also observed that this relation failed at sufficiently high rates of flow.

In 1880 Seelheim, by studying the flow through sands of different grain sizes, found that

$$v \propto d^2, \qquad (3)$$

where d is the mean grain diameter. To this Slichter (1899) added the effect of the fluid viscosity, whereby

$$v \propto \frac{1}{\mu}. \qquad (4)$$

Although Darcy's experiments were limited to flow in the vertical direction, it was soon realized that equation (1) was of general validity for flow in any direction. This was given analytical expression for general three-dimensional flow by Forchheimer (1914, p. 437), who expressed equation (1), which had long since become known as "Darcy's law," in the vectorial form

$$v = -K\nabla h. \qquad (5)$$

This signifies that the flow lines are everywhere normal to a family of surfaces h = Constant and in the direction of $-\nabla h$, the *hydraulic gradient*. He also pointed out that (for K constant), $\nabla^2 h = 0$.

Equation (5) may also be expressed in terms of the pressure gradient in the flow field by the use of the hydrostatic equation

$$p = \gamma g(h - z), \qquad (6)$$

where p is the fluid pressure at a given point of elevation z above a standard datum, h the

[1] Manuscript received May 17, 1950.

height with respect to the same datum of the fluid in a manometer terminated at the point of interest, γ the fluid density, and g the acceleration of gravity. Solving equation (6) for h gives

$$h = z + \frac{p}{\gamma g},$$

of which the directional derivative is

$$\frac{\partial h}{\partial s} = \frac{\partial z}{\partial s} + \frac{1}{\gamma g}\frac{\partial p}{\partial s}, \tag{7}$$

or the gradient is

$$\nabla h = \nabla z + \frac{1}{\gamma g}\nabla p\,. \tag{8}$$

Now if we multiply both sides of equation (8) by $-g$ and note that $|\nabla z| = 1$, we obtain

$$-g\nabla h = g - \frac{1}{\gamma}\nabla p\,, \tag{9}$$

which is a vectorial statement of the forces per *unit of mass* acting upon the fluid at a given point. Multiplying by $-\gamma g$ gives

$$-\gamma g\nabla h = \gamma g - \nabla p\,, \tag{10}$$

which are the corresponding forces per *unit of volume*. It will be noted, in particular, that the fluid-flow direction, $-\nabla h$, is, in general, parallel to neither of the vectors g or $-\nabla p$.

Now if we combine equation (9) or (10) with equations (3), (4), and (5) and discard the undefined constant K, we obtain

$$\begin{aligned} v = -K\nabla h &= \frac{Nd^2\gamma}{\mu}\left(g - \frac{1}{\gamma}\nabla p\right) \\ &= \frac{Nd^2}{\mu}(\gamma g - \nabla p)\,, \end{aligned} \tag{11}$$

of which the only physically undefined parameter is the residual factor of proportionality, N. A dimensional check will show that this is dimensionless and that it depends only upon the small-scale geometric shape of the flow system. Combining the two geometrical factors Nd^2 into a single factor k then gives

$$\begin{aligned} v = -K\nabla h &= \frac{k\gamma}{\mu}\left(g - \frac{1}{\gamma}\nabla p\right) \\ &= \frac{k}{\mu}(\gamma g - \nabla p)\,. \end{aligned} \tag{12}$$

These are three different expressions of Darcy's law, all of which are of general validity for flow in three dimensions and are entirely equivalent physically to Darcy's original formulation. Moreover, they are based exclusively upon work done before 1914. The hydraulic-gradient equation is obviously applicable only to liquids, but the last two forms are valid also for gases.

In the petroleum industry an awareness of the importance of Darcy's law as a basis for studies of fluid flow did not become widespread until about 1930, and the usage followed in the book under review dates from a paper by Wyckoff, Botset, Muskat, and Reed (1933) on the measurement of permeability. In this paper the pressure-gradient equation,

$$v_s = -\frac{k}{\mu}\frac{\partial p}{\partial s}, \tag{13}$$

was erroneously set forth as representing Darcy's law (compare with eq. [12]). This same paper also became the basis for Code 27 on the measurement of permeability, adopted in 1935 by the American Petroleum Institute, which, in effect, made equation (13) official for the petroleum industry as a supposed statement of Darcy's law.

This equation was given further currency when Muskat's book, *Flow of Homogeneous Fluids through Porous Media*, appeared in 1937. There, after correct statement of Darcy's law (p. 56) as given by equation (1) above, the pressure-gradient equation (p. 71) was again put forward as representing Darcy's law, and, eliminating any possible doubt as to what was meant, the two (p. 72) were equated to each other:

$$v = \frac{k}{\mu}\frac{dp}{dx} = \frac{k\gamma g}{\mu}\frac{dh}{dx} = \bar{k}\frac{dh}{dx}. \tag{14}$$

According to these equations,

$$\frac{dh}{dx} = \frac{1}{\gamma g}\frac{dp}{dx}, \tag{15}$$

which, by comparison with equation (7), is seen to be significantly in error.

Although later in the same book (p. 129) a flow equation of the correct form,

$$v_x = -\frac{k}{\mu}\left(\frac{\partial p}{\partial x} + F_x\right), \tag{16}$$

was derived, the pressure-gradient equation was repeatedly employed thereafter both in equations and in the text.

An alternative expression, supposedly ap-

plicable to any single-phase flow problem, was given by the velocity-potential equation (p. 129),

$$v = -\nabla\Phi\,, \qquad (17)$$

where $\Phi = k/\mu(p - V)$ and V is the potential of a field of force (per unit of volume), $\boldsymbol{F}$.

Critics (Richards, 1940; Hubbert, 1940, 1941) soon pointed out that the pressure-gradient equation is not an expression of Darcy's law and that, in view of the fact that fluids can flow from lower to higher pressures quite as readily as in the reverse direction, it obviously is not physically valid. They showed, moreover, that the true Darcy's law is that expressed by equation (12) or any equivalent expression. It was also shown (Hubbert, 1940, pp. 903–909) that in all but special cases the velocity vector $\boldsymbol{v}$ is rotational and not derivable from a velocity potential.

The erroneous statement of Darcy's law in Code 27 was also called to the attention of the American Petroleum Institute, and in 1942 (A.P.I., 1942) that code was revised to the extent of abandoning the pressure-gradient equation and replacing it by the correct equation,

$$v_s = -\frac{k}{\mu}\left(\frac{\partial p}{\partial s} - \gamma g \cos\theta\right), \qquad (18)$$

where θ is the angle between s and the direction of gravity.

The next development in this sequence is the book under review: *Physical Principles of Oil Production*. Here the subject of fluid flow is introduced (p. 124) not by the usual pressure-gradient equation but by equation (18) above. This, however, is stated not to be an expression of Darcy's law but a generalization of that law (due to Muskat), rendering it valid for flow in three dimensions and also applicable to different fluids. Darcy's original law, one reads on pages 184 and 185, is given by

$$v = -\frac{k}{\mu}\nabla p\,. \qquad (19)$$

This viewpoint is further elaborated in various parts of the text, of which the following passage (p. 124) is representative:

> The second generalization pertains to the inclusion as measures of the driving force both *pressure* and *hydraulic gradients*. Naturally only the latter were considered by Darcy, who experimented exclusively with water. While, strictly speaking, in the oil industry gravitational or fluid-head forces are almost universally present as driving agents affecting the movement of oil, gas, and water, in the great majority of practical oil-production systems *the predominating driving forces are those due to fluid pressure gradients*. . . . Accordingly the above statement of Darcy's law implies that *pressure gradients and hydraulic heads are equivalent, interchangeable, and superposable* [italics mine].

In view of the correct relations between pressure and hydraulic gradients set forth in equations (7) and (8) above, a more confused statement concerning these quantities would be difficult to make. As to the dominance of forces due to pressure gradient in oil production, calculations on this point indicate that, for an average-producing oil well in the United States, the ratio of the pressure-gradient force to that due to gravity becomes of the order of unity at a distance away from the well of less than 10 feet.

From the foregoing and similar statements it becomes evident that the same lack of understanding which in 1933 led to the representation of the pressure-gradient equation as Darcy's law, and in 1937 to the writing of equation (14) above, still persists. A correct statement of Darcy's law (eq. [18]), which, in substantially that form, has been in use for half a century, is now presented as a new generalization of that law, rendering it valid for flow in three dimensions, whereas the pressure-gradient equation, for which Muskat and his associates are solely responsible, is credited to Henry Darcy!

If the confusion resulting from calling unlike things by the same name is to be avoided, it is apparent that a separate name for the pressure-gradient equation is needed to distinguish it from Darcy's law. Since this equation owes its prominence to its extensive use by Muskat, it would therefore appear fitting that the equation

$$v = -\frac{k}{\mu}\nabla p\,,$$

or any of its physical equivalents, should hereafter be known as "Muskat's law."

This might be of only academic interest, were it not for the fact that the physical confusion indicated is recurrent throughout the book. On page 193, for instance, it is stated that "the nature of the fluid enters Darcy's law only through its viscosity," and, further, "the fluid density does not enter in the 'law of force' equation." On pages 194 and 195 the problem of the flow through a uniform sand of constant thickness into a well completely penetrating the sand

is discussed. It is stated that, since gravity effects are not involved, the system will be described by Laplace's equation in the fluid pressure; and the solution obtained comprises a family of equipressure surfaces, coaxial with the well and perpendicular to the lines of flow. This result is physically false, and the actual equipressure surfaces (since gravity does enter in the problem) are a family of coaxial trumpet-shaped surfaces, divergent and convex upward, which rapidly approach horizontality with increase of distance from the well. This error is repeated on pages 242 and 243 in a discussion of the flow with radial variations of permeability.

On page 540 the flow equation for a compressible liquid is stated to be:

$$\gamma v = -\frac{k}{\mu}\gamma\nabla p = -\frac{k}{\mu\kappa}\nabla\gamma\,, \qquad (20)$$

according to which the flow lines would be orthogonal with the equipressure and equidensity surfaces and the flow rate proportional to the respective density and pressure gradients—a result in accord with theoretical deductions on pages 187 and 188 but still physically invalid.

The pressure-gradient equation is again implied in the statement on pages 764–765 concerning the analogy between electrical and fluid models:

> For homogeneous two-dimensional systems, of constant thickness, the basic analogy between the electrical model and the flow system simply rests on the observation that the *electrical potential* corresponds to the *pressure* [italics mine] and the current density to the fluid flux.

The theoretical development of the flow equations and an explanation of the methods to be used in solving flow problems are presented in chapter iv. This begins with a statement of the equation of continuity for fluids with different equations of state. Next, the equations of Navier and Stokes are written but are discarded on the grounds that they cannot be solved. Finally, the "generalized" Darcy's law is given (p. 185) as

$$v = -\frac{k}{\mu}(\nabla p - \boldsymbol{F})\,, \qquad (21)$$

where $\boldsymbol{F}$ is a force ("such as gravity") per unit volume.

This is a correct statement of Darcy's law in the form of the third of equations (12), above. It is of general validity for flow of both compressible and incompressible single-phase fluids in three-dimensional space, and, were it consistently and correctly employed, together with the appropriate equations of state, it would lead consistently to correct results.

Equation (21), however, is seriously restricted by the next step. A "velocity potential," Φ, is defined by

$$\Phi = \frac{k}{\mu}(p + V)\,, \qquad (22)$$

whereby

$$v = -\nabla\Phi\,. \qquad (23)$$

Here V is the potential of the force $\boldsymbol{F}$, and on page 187 the value of V for incompressible and compressible liquids, respectively, is given by

$$\begin{aligned} V &= \gamma g z, \\ V &= g\int\gamma d z\,. \end{aligned} \qquad (24)$$

As contrasted with the statement in the earlier book that equation (23) is of general validity, it is now admitted to being valid only for the flow of a fluid of constant viscosity in homogeneous and isotropic media.

Since gravity is known to have a potential, the potential V of the force $\boldsymbol{F}$ is likely to pass unnoticed. It happens, however, that the gravitational-field intensity at a point can be defined uniquely only in terms of a *force per unit of mass* and not in terms of *force per unit of volume*. It is the former which in all cases has a potential. When the density is constant, the force per unit of volume, $\boldsymbol{F}$, also has a potential, as given by the first of equations (24). When the density is variable and the equidensity surfaces are not horizontal, which is, in general, the case for a fluid in motion, the force $\boldsymbol{F}$ has no potential, since V in the second of equations (24) in this case is a function of the path of integration. Hence the insertion of V in the equations for compressible fluids on page 186 and elsewhere is not justified.

A closely related error occurs in several places when the flow of multiphase fluids is discussed. For example, on page 274, the flow equation for the gas phase in a water-gas-oil mixture is given by

$$v_g = -\frac{k_g}{\mu_g}\nabla(p - \gamma_g g z)\,. \qquad (25)$$

Since γ_θ is variable, expansion of the gradient of the terms in parentheses gives

$$\nabla(p - \gamma_\theta g z) = \nabla p - \gamma_\theta g \nabla z - g z \nabla \gamma_\theta , \quad (26)$$

which is significantly different from the correct force terms in equation (21).

On pages 186–190 the "equations of motion" are obtained by combining the Darcy's law equation with the equations of state and of continuity. For incompressible fluids and homogeneous media this leads (p. 187) to

$$\nabla^2 p = 0 = \nabla^2 \Phi . \quad (27)$$

For compressible liquids the equation first obtained (p. 187) is

$$\nabla \cdot \left(\frac{1}{\kappa} \nabla \gamma + \gamma^2 g \nabla z \right) = \frac{f \mu}{k} \frac{\partial \gamma}{\partial t} . \quad (28)$$

Here κ is the compressibility defined by

$$\gamma = \gamma_0 e^{\kappa p} , \quad (29)$$

and f is the porosity. Then by a circular argument it is reasoned that the second term, $\gamma^2 g \nabla z$, of equation (28) is of a negligible magnitude as compared with the first, $\nabla \gamma / \kappa$, leading to the desired result (p. 188),

$$\nabla^2 \gamma = \frac{f \kappa \mu}{k} \frac{\partial \gamma}{\partial t} . \quad (30)$$

This is the basis for equation (20), above, quoted from page 540. A similar equation is given for gases (p. 189) in terms of $\nabla^2 \gamma^{(1+m)/m}$, where m is the ratio of the specific heat at constant volume to that at constant pressure.

The fallacy in this procedure lies in the fact that the compressibility of a fluid is in nowise dependent upon the pressure gradient or the state of motion. Hence an equation of motion for a compressible fluid must retain its validity when the fluid is at rest or in very slow motion, which is the usual state for underground fluids. Under these conditions the two terms of equation (28) are of comparable magnitudes, and the fluid may flow in any direction in space with respect to the direction of the density gradient.

The procedure for solving flow problems is outlined on pages 189 and 190. Laplace's equation ([27] above) is taken as the basis for solving problems in the steady-state flow of liquids. The geometry of the space, initial pressure or density distributions, and the boundary conditions (pressure, velocity potential, density, or their normal gradients) are to be assigned. Then with the *appropriate equation of motion* the problem is to be solved as a boundary-value problem.

This procedure is sound, *provided* that proper initial and boundary conditions are assigned and valid equations of motion are employed. The importance of this provision is illustrated by the radial-flow problem of pages 194–195, already mentioned. Here radial flow is assumed to start with, and the pressure is assumed correctly to satisfy Laplace's equation. However, by assigning an erroneous boundary value p = Const. in the well, an erroneous solution for p in space is obtained, and this can then be reconciled with the assumed flow field only by means of an erroneous flow equation.

In the light of this recital it is evident that the problem of appraising the book under review is complex. As to style and composition, it is meticulously written. The chapter on the physical properties of petroleum fluids is good. The mathematical treatment of boundary-value problems, considered as abstract mathematics without regard to the physical validity of the equations, is also good. Moreover, in many instances correct physical relations have been employed.

Despite all this, the fact remains that, with respect to the physical theory of the flow of fluids through porous rocks, a wrong turn was taken by this author and his colleagues in 1933, which was adhered to in his book *The Flow of Homogeneous Fluids through Porous Media*. During the twelve years which have elapsed between the publication of that book and its present revision and extension, there has been ample opportunity to rectify earlier errors and to bring the physical theory to the same level of excellence as the rest of the treatment. But this has not been done.

In consequence of this default the usefulness of the book is severely limited. For those who already have sufficient knowledge of the physics of fluid flow through porous rocks to supply the necessary corrections, this work is a useful reference; but for students and others who have not such knowledge and who, on the basis of its credentials and sponsorship, assume the book to be an authoritative treatise, the result can hardly be other than the perpetuation of a state of confusion which has already persisted too long.

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REVIEWS

Introduction to Historical Geology. By RAYMOND CECIL MOORE. New York: McGraw-Hill Book Co., 1949. Pp. ix+582; figs. 364. $5.00.

As a conventional elementary narrative of American geologic history this book is similar to most currently popular texts. The format is attractive and the photographs excellent. But the more important quality—approach to subject matter—seems to this reviewer to fail to meet the author's own standards.

In his Preface Dr. Moore points out that even beginning students need to understand *evidence* of past conditions and geologic events in order to comprehend their present surroundings and appreciate the immensity of geologic history. Concerning the object of elementary geology, he says that "to think accurately and make sound analysis of any set of observations are abilities that a student needs much more than the ability to repeat something he has memorized."

In trying to attain these objectives he has failed to take much advantage of the problem-solving approach which he had previously recommended so strongly in the Preface to his more advanced *Historical Geology* (1933). In order to provide examples for students to follow in applying principles in new situations, he stated that he favored presenting, first, the concrete observations and then the reasoning by which tentative hypotheses are suggested and tested. Once a conclusion is reached, the student should know the basis for it and should recognize uncertainties and unsolved problems. Illustrating his statement that a study based on a specific area is better than elaboration of principles in abstract form, the introductory chapter of Moore's advanced text on "The Historical Significance of Rock Characters" went through this whole procedure for the Grand Canyon district, utilizing historically important data to reach conclusions on the stratigraphic, structural, and geomorphic history of the region. The basic concepts of uniformitarianism, superposition and correlation, unconformities, and geologic time were developed from the facts at hand, and their broad significance was well illustrated.

These means seem very appropriate to the end of training in thinking and understanding, but they are almost completely abandoned in the present book. The principles of historical interpretation and biological evolution are asserted in a systematic outline in the first two chapters without any problem buildup. When concrete examples are provided, they generally follow or accompany, instead of precede, the general principle or concept.

The rest of the book consists mostly of historical narration of data and interpreted events and "cause-to-effect relations," but it, too, is conspicuously lacking in the "effect-to-cause" reasoning by which the latter were inferred. Because general principles have supposedly been "covered" already, they are not developed from history as it unfolds or used to bring the many events into a rational order. This would be difficult in any book bound by the period-per-chapter organization, inasmuch as principles of continental and biological evolution emerge only from consideration of one or more areas over longer intervals. The almost stereotyped outline of each chapter (type region, North American rocks, paleogeography and sedimentation, life, climate, and close of the period) makes little pretense of organizing around the development of problems, large or small.

Paleontological history by phyla is summarized in separate chapters at the end of the presentation of each era but is not selected for significance in terms of evolutionary or ecological principles (supposedly finished in chap. ii). These chapters, plus one on man, and a systematic morphological appendix are added to separate hasty accounts in chapters for each period. As the author once commented (1933), "repetition of this treatment in a dozen or more successive chapters almost inevitably leads to confusion and mental indigestion, the extent of which depends on the attitude and scholarship of the student."

In an apparent effort to simplify memorization, contemporaneity of correlations and unconformities and other uncertainties are glossed over easily, at the expense of giving a cut-and-dried picture of geologic history (and geology

itself). Although lacking the reality of measured sections, the generalized stratigraphic charts do include desirable suggestions of facies change, overlap, offlap, and time gaps. But these implications are hardly mentioned explicitly or used in interpreting the events and principles which they represent so well.

There is one good example of the problem approach, worthy of study as a guide for future improvement. Interpretation of the St. Peter sandstone is derived, if only briefly (pp. 4–6), *from* the data on texture, composition, structure, and distribution *by* explicit logical analyses of alternative hypotheses *to* a qualified interpretation of agent and mode of transport and deposition, illustrating the general criteria for making such interpretations. This might be expanded and extended to general concepts of sediment maturity, recurring lithotypes, possible facies change and overlap, source problem, general paleogeography, and cratonic stability characterizing the interior during the rest of the Lower Paleozoic. A few more good examples and general comparisons of columns should dispose of this much history with more significance and interest and probably more fact retention than the standard presentation, aside from the main objective of showing approach. Such criteria, interpretations, and principles might be contrasted with coal measures, Appalachian geosynclinal graywackes and delta deposits, and postorogenic Newark facies. Once a few examples provided direction and tools, students could be given increasing independence in approaching increasingly complex and comprehensive problems, at whatever rate suited them.

Although this book, like most other historical geology texts, is oriented far from the direction explicitly favored by Moore, we owe him a great debt for pointing out that direction and stimulating exploration of new approaches for the sake of future teaching and progress in the field of geology. His statement, "the means of arriving at conclusions concerning earth history are more important than the conclusions themselves," applies not only to the future geologist but especially to the liberal arts student. Explicit training in "sound analysis of any set of observations" not only is necessary for making everyday or vacation-time applications of geology but can be extended to help solve a great variety of important problems in modern life.

JERRY OLSON

University of Chicago

Subsurface Geologic Methods: A Symposium. Compiled and edited by L. W. LEROY and HARRY M. CRAIN. (*Colorado School of Mines Quarterly*, vol. 44, no. 3.) 1949. Pp. 826; figs. 436; pls. 12. Paper binding, $6.00. (Independent publication, Colorado School of Mines, 1949. Fabrikoid binding, $7.00.)

A comprehensive and uniformly good book has been produced by the editors of this volume. A wide range of subjects, adequately covering the field, is presented, and the danger of overemphasis and biased treatment of new controversial material has been avoided through careful selection and editing. The book will serve as both a reference and an advanced text for the petroleum geologist and will be valuable to other specialists, sedimentary petrographers and engineering geologists in particular.

The coverage of the field is indicated by the following list of major topics: stratigraphic, structural, and correlation considerations; micropaleontologic analysis; detrital mineralogy; insoluble residues; thin-section analysis; petrofabric analysis; screen analysis; settling analysis; stain analysis; shape analysis; porosity and permeability analysis; electron-microscopic analysis; water analysis; X-ray analysis; core analysis; multiple-differential thermoanalysis; lithologic logging; electric logging; induction logging and application to logging of wells drilled with oil-base mud; radioactivity well-logging; caliper and temperature logging; well-logging and drilling-mud and cuttings analysis; spectrochemical sample logging; drilling-time logging; fluoroanalysis; driller's logging; composite-cuttings analysis logging; controlled directional drilling; oil-well surveying; magnetic core orientation; oriented cores; dipmeter surveys; coring techniques and applications; design and application of rock bits; deep-well camera; the electric pilot in selective acidizing, permeability determinations, and water locating; character of pores in oil sand; subsurface graphic representations; subsurface maps and illustrations; reports on subsurface geology; subsurface methods as applied in geophysics; subsurface methods as applied in mining geology; and geologic techniques in civil engineering.

It is impossible in a brief review to comment on many of the details of the book. The reviewer agrees with the announcement made by the publishers that the volume represents a distinct contribution to the literature of subsurface geologic procedures, by including in one source dis-

cussions of methods in detail that have heretofore been unavailable or scattered. The text is well documented with selected references.

The chapters on "Subsurface Graphic Representations" and "Subsurface Maps and Illustrations" appear worthy of special comment, since they give a more extensive and excellent presentation of their subjects than can be found in any volume of similar scope.

Mechanically, the book is an excellent product, printed in large type on good paper. Almost without exception the illustrations are unusually clear. Copies of the paper-bound edition probably will not stand the use to which they are likely to be subjected.

J. L. HOUGH

University of Illinois

Rock Alteration as a Guide to Ore—East Tintic District, Utah. By T. S. LOVERING *et al.* ("Econ. Geology Mon.," no. 1.) 1949. Pp. 64; figs. 12; pls. 5. $2.50.

The Society of Economic Geology is fortunate in having a timely topic, such as rock alteration, for the first number of their new monograph series. Lovering and collaborators have carried on detailed alteration studies in the East Tintic district for several years as a part of the U.S. Geological Survey program of mineral deposits, and this monograph is the first presentation of their data and conclusions.

Five stages of alteration have been recognized: (1) early barren stage, marked by dolomitization of limestone and chloritization of lavas; (2) mid-barren stage, distinguished by argillic alteration that is most extensive in the volcanic rocks; (3) late barren stage, characterized by jasperoid and pyrite localized near major channels of mineralization; (4) early productive stage, indicated by the introduction of potash and deposition of pyritohedral pyrite near the ore bodies; and (5) the productive (ore) stage, marked by abundant precipitation of sulfides, sulfantimonides, and sulfarsenides and some tellurides and gold. The distribution of these altered zones with respect to the ore bodies and intrusive monzonite porphyry is shown graphically by four plates in color and four figures. Losses and gains of constituents during alteration are clearly demonstrated by bar graphs, and Lovering is to be congratulated for this simple and effective graphical presentation. Unfortunately, some of the lettering on two figures is too small for easy legibility.

A most useful table presents the optical properties of some secondary minerals associated with ore deposits. The geologist who has been slightly confused by papers referring to "hydromica," "hydromuscovite," and "sericite," without any statement as to criteria for separation, will be grateful for Lovering's clear-cut statements of the properties of these minerals. Thermal analysis curves of some of the secondary minerals are a welcome addition.

Lovering's discussion of the geochemistry of the mineralizing solutions should interest many geologists not directly concerned with ore-finding. However, the field geologist will be tantalized by the following statement: "Studies of the field occurrence, consideration of the chemical changes involved, and a review of the geological and chemical literature have led the writer to ascribe the dolomitization to hot dilute solutions of mixed chlorides ($MgCl_2$ and minor $CaCl_2$) with some CO_2." A more complete presentation of these factors would add to the treatment of the geochemistry.

This monograph on alteration is a welcome addition to the literature on ore deposits and is highly recommended to all economic geologists, petrologists, and mineralogists. Although Lovering presents the thesis that in the Tintic district the various alteration zones are formed by differing solutions separated by appreciable time intervals, he recommends that the interested reader should refer also to "Wall Rock Alteration at Butte, Montana," by R. H. Sales and Charles Meyer (*Am. Inst. Min. Met. Eng., Tech. Paper 2400* [1948]) for an excellent presentation of evidence indicating that the hydrothermal alteration at Butte is essentially contemporaneous with ore deposition and that the different zones may be reaction rims of the ore-depositing solutions.

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The Ellenburger Group of Central Texas. By PRESTON E. CLOUD, JR., and VIRGIL E. BARNES. ("University of Texas Publications," No. 4624 [June 1, 1946].) Austin, December, 1948. Pp. 473; pls. 45; figs. 8; tables 3. Paper, $5.00; cloth, $6.00.

Excellent critical work on the outcropping Ellenburger rocks, Lower Ordovician carbon-

ates, which began with that of Dake and Bridge in 1932, is presented in this report on the final results of continuous co-operative work by geologists of the Texas Bureau of Economic Geology and the U.S. Geological Survey between December, 1943, and June, 1946. It is a basic study of Ellenburger rocks, with emphasis on features of possible significance to the search for new sources of petroleum, prompted in part no doubt by the fact that Ellenburger strata are important petroleum reservoir rocks in western Texas. Many data given in preliminary reports are repeated for the sake of completeness, and some portions are taken bodily from previous papers, with appropriate revision.

The report is divided into three parts, which separate purely documentary detail from general descriptions and conclusions. Part 1 comprises information on the Ellenburger group of central Texas as a whole. The writers here discuss the stratigraphy of the Ellenburger and pertinent details of the rocks that overlie and underlie it, consider some regional correlations, speculate on the probable origin and paleoecology, and sumarize the geological history, paleontography, geological structure, petrography, and economic resources of the Ellenburger group. The basis of correlation is summarized, selected technical terms defined, and methods, techniques, and other subjects of general interest are discussed briefly.

Detailed descriptions and discussion of numerous stratigraphic sections comprise part 2. Thoroughness of field work and description of sections is such that the sequences can be readily located and followed. Part 3 presents supplementary data of various sorts, including lists of Lower Ordovician and Upper Cambrian fossils in the Arbuckle and Wichita Mountains, Oklahoma; chemical data; and description of thin sections.

In addition to the comprehensive store of information on the Ellenburger group, interesting information is presented on the Devonian and Mississippian rocks in central Texas and correlations with equivalent outcropping rocks in trans-Pecos Texas.

Numerous illustrations, including geological maps (two colored), stereograms, and plates of fossils, and a comprehensive Bibliography add materially to the usefulness of this report.

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La Genèse des montagnes. By MARCEL ROUBAULT. Paris: Presses universitaires de France (108 Boulevard Saint-Germain). ("Séries la science vivante.") 1949. Pp. ix+243; figs. 51.

In the Preface Professor Roubault states that he was impelled to write this book on the origin of mountain ranges by his dismay over the ignorance of geology of many educated people as well as students of the natural sciences, and also by his dissatisfaction with the dry, uninteresting manner in which geology is taught in some cases. To offset this, he set himself the task of writing an outline of one of the most difficult, controversial, albeit fascinating, geological problems. The pages of this pocket-sized book are small, there are only fifty-one text figures, no folded maps or charts, no plates, not a single photograph of a geological object. Yet, despite these limitations—dictated, we supposed, by economy—the book is interesting reading that can be recommended not only to the layman but also to geologists who wish to go over this field.

The author starts with fundamental facts about the earth, its specific gravity, chemical composition, the hypothetical structure of the interior and the crust as inferred from seismic and related methods of determination, which are outlined. This is followed by a discussion of gravity anomalies, how they have been determined, and what has been inferred from them. Belts of negative anomalies and the rise of Fennoscandia are stressed. Thermal problems of the globe conclude this chapter.

Consideration of the earth's surface relief brings the author to mountain ranges and their folded structure. The remarkable nappes of the Alps are emphasized as they raise the problem of how far crustal blocks may have traveled horizontally. The author touches briefly on older theories of mountain-building and discusses in more detail the drift theory. He is favorably impressed by many aspects and arguments of it, but advocates comprehensive discussion of all facets of this problem before the theory is either accepted or discarded.

Griggs's mechanism of large-scale convection currents in subcrustal cells is portrayed. The author agrees that the currents would serve admirably to explain the structure of folded mountain ranges, but he is dubious about the nature of the motivating force. This, he believes, may be provided by extrapolating R.

Perrin's observations on the growth of lime-silicates and other inorganic compounds in the walls of furnaces, due to dry diffusion, without the aid of fluids. He points out that if a unit volume of silica should take on, through diffusion, enough alumina and potash to make orthoclase, this would cause a volume increase of 55 per cent. Following Perrin, the author assumes that in the deeper portions of the crust reactions of this kind occur commonly enough, and on so large a scale, that they can raise appreciably some crustal belts. The reviewer regrets that the author does not describe the limiting conditions under which such reactions are possible. The presence of H_2O, found in virtually every rock analysis, seems effectively to suppress the kind of reaction here envisaged; no quantitative calculation is given to show that volume-increasing reactions due to dry diffusion may not be counterbalanced by volume-reducing ones; nor does the reader learn why dry diffusion should take place along a particular crustal belt and should proceed more rapidly during some periods than during others.

At any rate, if a crustal belt should be raised through the mechanism assumed by Perrin, or any other, then, the author believes, the difficult nappe problem can be solved without recourse to Argand's speculations of long-distance gliding. He refers to observations by Haarmann, Lugeon, and others on submarine gliding of incompletely consolidated sediments on the ocean floors, caused presumably by tilting of the floor beyond a critical value. He considers that systems of superposed nappes, like those of the Alps, may have formed through some such rise of an axial zone and successive large-scale slippage of the sedimentary cover. Obviously, the innumerable complex side issues of this problem cannot be taken up in detail in this book, so that the reader is likely to finish reading this chapter unconvinced and a bit bewildered but aware that he has been brought closer to the intricacies of an intriguing problem from which many dogmas have been discarded and more adequate theories will develop as we learn more about the properties and true structure of the earth's crust.

The book closes with comments on experiments on rock deformation. The author pleads for better observance of scale reduction, and stresses the importance of creep tests.

References in the book are few but apt and include French and foreign papers up to 1947. The author's style is simple and easy to follow. The book is likely to find many readers among students of tectonics.

ROBERT BALK

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The Study of Rocks. By S. J. SHAND. 2d ed., rev. New York: Thomas Murby & Co., 1947. Pp. xi+236. 10*s*. 6*d*.

This work was first published in 1931 as a book primarily for students beyond the beginner stage. The contents are largely descriptive and cover igneous, sedimentary, and metamorphic rocks. In its second edition we find the book somewhat revised but only slightly enlarged. Most of the changes have been made to bring the book more up to date; other changes are supplementary in nature. The appendix on chemical analysis of rocks, which was quite inadequate in the first edition, has been extended from three to twelve pages.

One admirable feature of the text is the emphasis which the author places on the value of field observation in rock study and the attention that he calls to the fact that petrologic problems cannot be solved solely with the microscope. Much space is devoted to the geological occurrence of rock types.

One chapter deals with the classification of eruptive rocks. Here about ten different systems are critically discussed. In the chapters on rock description the author outlines for the student the complicated problem of nomenclature, pointing out the many errors, inconsistencies, and differences of opinion which have given rise to much confusion in terminology. He then proceeds to show how simple the problem becomes by the adoption of his logical, practical, and theoretically sound classification. The rocks are described, and typical examples of each kind are given; many such examples are from classical areas. Throughout the text considerable attention is given to problems of petrogenesis.

This little book gives a wealth of background material even for the more advanced student in geology, and at the end of each chapter is an excellent list of suggested readings.

A few suggestions and remarks might be made. On page 13 the discussion of composite sills and dikes will be somewhat confusing to most American students and perhaps to most British students as well. The author discusses what would normally be called differentiated

bodies but fails to distinguish them from composite structures. Furthermore, the reviewer cannot quite agree with the author that magmatic differentiation is not a process.

Only slight revision would have been necessary to bring the discussion of Johannsen's classification up to date.

The description of rock-forming minerals is more up to date than that of most texts on petrology and even mineralogy at a similar level published in English. Nevertheless, it seems certain that, if this treatment could have been carried even further, it would have greatly warranted the additional space required. Cristobalite, a rather important constituent of silicic volcanic rocks, is not mentioned. Might not the terms "fluorite," "hauynite," and "idocrase" be preferable to "fluorspar," "haüyne," and "vesuvianite," respectively?

It is felt that the inclusion of more material on structures and microstructures of rocks would have added much to the value of the text without adding greatly to its length. Many common terms in these categories are not even mentioned. A more detailed treatment of pegmatites and aplites seems justified.

The quality of paper used and the binding are good; the printing is very good, and only a few typographical errors were noted.

CARLETON A. CHAPMAN
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Die Bergwirtschaft der Erde—Bodenschätze, Bergbau und Mineralienversorgung der einzelnen Länder ("World Mining—Mineral Resources, Mining, and Mineral Supplies of the Individual Countries"). By FERDINAND FRIEDENSBURG. 4th ed. Stuttgart: Ferdinand Enke Verlag, 1948. Pp. xiv+574; figs. 56. Dm 58.

For many years Dr. Friedensburg has covered the field of mining statistics for the German Geological Survey, and the first edition of this book was published in 1938, but later ones were issued during the war years. Friedensburg's book is similar in scope to Roush's *The Mineral Industry*.

A few introductory pages define the scope of the book and outline modern industrial trends and war demands that have vitally affected the development and expansion of world mining. Each country is then taken up in alphabetical order. The principal resources are noted, and significant developments, discoveries, or mining methods are stated as far as known. Selected references are given at the end of the description of each country. Production figures of the more important commodities are given in charts, and numerous text figures illustrate the distribution of mining districts.

For obvious reasons, the author has been unable to cover completely the more recent literature, but, he states, the demand for a new edition became so great that he decided to publish the present book despite these shortcomings. At the end of the description of countries, world production statistics of the principal commodities are given in numerous charts, and an Index of nineteen pages concludes the book.

ROBERT BALK
University of Chicago

The Outline of the Geology of New Zealand (To Accompany the 16 Mile to 1 inch Geological Map). By OFFICERS OF THE GEOLOGICAL SURVEY. New Zealand Department of Scientific and Industrial Research, Geological Survey Branch, 1948. Pp. iii+47. 6*s*. 1*d*.

This condensed summary of the geological formations now recognized by the New Zealand Geological Survey describes briefly each of the formations shown on the new colored map. This comprises two sheets, each measuring 40 × 30 inches. Twenty-three formations have been designated by different colors. Culture and town names are printed in gray, most of the colors are pleasing pastel shades, and the registration is very good. Formations are numbered in the map, and the legend connects figures and colors with the appropriate formation names and ages. The usefulness of the map could have been somewhat enhanced if strike and dip symbols had been added here and there, and, of the many faults, only the large Alpine Fault is easily seen as it divides the southern island longitudinally into two parts. Other faults have been mapped but are not shown by heavy lines.

In the *Outline* each division is described briefly with reference to lithology, distribution, and age assignment. The oldest rocks of known age range from Ordovician through Devonian. They crop out in small areas in southernmost New Zealand only. Here also is found the extensive complex of metamorphosed rocks in which fossils of late Paleozoic and early Mesozoic age have been discovered at a few places. Nearly

half the islands are underlain by the thick geosynclinal sediments of Cretaceous and Cenozoic age. Fossils are more abundant than in the pre-Cretaceous rocks and permit much closer subdivision and correlation with other areas.

Selected references are given at the end of each chapter. Emphasis is on the stratigraphy of the islands, and only seven pages are devoted to the igneous rocks and structure of New Zealand. Even so, the reader will be impressed by the remarkable similarity between the geology of New Zealand and that of the North American Coast ranges.

ROBERT BALK

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Copper in California. Prepared under the direction of OLAF P. JENKINS. (State of California Department of Natural Resources, Division of Mines Bull. 144 [December, 1948].) Pp. 429; figs. 23; pls. 9+61 folded pls. in separate container; tables 19; economic mineral map of California.

Copper in California consists of (1) detailed reports on certain deposits of the Foothill Copper-Zinc Belt (147 pp.), (2) a discussion of the marketing, milling, and metallurgy of complex iron-copper-zinc sulfide ores (36 pp.), and (3) a tabulated list, by counties, of the known copper deposits in all California (159 pp.), and a bibliography of the geology, economics, mining, milling, and metallurgy of California copper ores (29 pp.). There is also a very complete Index (41 pp.). A separate map-container holds 52 maps depicting the geology and mining of the Foothills Belt deposits, and the 1:2,500,000 Economic Mineral Map of California No. 6 (copper).

The title, *Copper in California*, is somewhat misleading because the deposits described are only some of those of the Foothills Belt. The important copper deposits of Plumas and Shasta counties are mentioned only very briefly in the discussion preliminary to the tabulation in part 3. The first section includes an outline of the geology of the Foothills Belt, an area which extends some 250 miles among the western foothills of the Sierra Nevada from Butte County on the north to Fresno County on the south. The history of the district began in the Civil War, and, up to the present, a little over one hundred thousand tons of copper and about one-fourth as much zinc have been mined. The deposits lie in folded and faulted Paleozoic and Jurassic rocks, which constitute the older of the two main groups in the Foothills Belt. They are mainly lenticular pyrite, chalcopyrite, sphalerite ore bodies, formed by replacement along lines of faulting, shearing, and crushing and surrounded almost always by strong zones of hydrothermal alteration. Structures formed in the Upper Jurassic orogeny localized much of the ore deposition which occurred after the regional metamorphism and the emplacement of the Sierra Nevada batholith. The spatial distribution of the deposits suggests that they are genetically related to the batholith.

This general treatment is followed by detailed discussions of the geology of those mines in the belt which were studied by the U.S. Geological Survey in the strategic mineral investigations of World War II. These fall into four major mineral types: (1) pyrite, sphalerite, and chalcopyrite, with a little galena and appreciable gold and silver; (2) pyrrhotite and chalcopyrite, with or without sphalerite and pyrite and usually with some gold and silver; (3) pyrite and chalcopyrite, with practically no gold, silver, or zinc; and (4) chalcopyrite, pyrite, and quartz, with or without sphalerite and generally with some gold and silver. The deposits characterized by pyrrhotite are most prominent in the southern part of the belt, where the main mass of the batholith is closest. The ore bodies highest in zinc lie at the greatest distance from the batholith.

Part 2 explains the disadvantageous economic position of California base metal deposits vis-à-vis those of other parts of the country but points out that accelerated industrial development in California promises ample markets if enough ore can be found and freight tariffs reduced sufficiently to justify local smelting. The milling and metallurgy of copper and zinc ores are taken up, with the former being presented in more detail than the latter.

Part 3 begins with a discussion of the distribution of copper in California, pointing out that California, seventh among the copper-producing states, produced 1.86 per cent of United States copper from 1845 to 1945. The distribution of the state's copper deposits is clearly shown on the appended Economic Mineral Map (No. 6, Copper), with symbols indicating the tonnages produced by each through 1946. This section is followed by a list of the copper minerals of California and a résumé of the geology of the copper districts of the state. Then a tabulated list, by counties, of copper mines, prospects, and

occurrences takes up about the next 150 pages (one-third of the book). Published material dealing with these is noted in the table by reference to the Bibliography, which follows it and so constitutes an index to the bibliographic part of the work, which is not included in the main index. The bibliography appears to be remarkably well chosen and complete.

This volume joins the long list of valuable contributions that have resulted from the cooperative work of the U.S. Geological Survey and the various states. The illustrations and maps which accompany the report are well done and add greatly to the value of the text. The state of California and the federal survey are to be congratulated on having produced a report of interest and value to all mining geologists and mine operators concerned with the production of copper. It is to be hoped that the similar project to investigate the Shasta copper belt, now currently being carried out under the same auspices, will shortly be brought to completion, as it will go far to round out the picture of copper in California.

JOHN RIDGE

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The History of Nature. By C. F. VON WEIZSÄCKER. Chicago: University of Chicago Press, 1949. Pp. vi+192; pls. 8. $3.00.

Although this could hardly be called a geological book, it is one that may well be read with great profit by every geologist. Professor von Weizsäcker, of Göttingen University, is one of Germany's most brilliant astrophysicists, and in this compact volume he surveys the entire field of natural science with deep philosophical insight. The text has been translated from the German, in which it was first published, by Fred D. Wieck, and it reads precisely as though it had been originally composed in English. Doubtless the author's own familiarity with the English idiom contributed much to this somewhat unusual achievement.

The style of presentation is informal and conversational. Evidently the author is addressing himself to the ordinary run of college students or to the average adult reader of nontechnical literature. Yet he does not pull his punches or dodge the really profound issues that inevitably arise. Instead he grapples incisively with the somewhat thorny problems that must be faced by any well-trained scientist who recognizes his responsibilities as a citizen of the world as well as a researcher in the laboratory.

The flavor, objective, and undergirding motive of the book are revealed in the introductory chapter:

> Instrumental knowledge is knowledge of fragments, and is content with that. It can be satisfied with a science that is completely specialized. Insight, on the other hand, I would call that knowledge which considers the coherence of the whole. Insight must be especially concerned with man himself, his motives and his aims, and with the inner and outer conditions of his existence. Insight may not separate subject and object fundamentally, but must recognize their essential kinship, their mutual dependence and, consequently, their inseparable coherence.

So far as the geologist is concerned, per se, attention might well be called to Von Weizsäcker's comments on the causes of mountain-building and glacial climates, brief and generalized though they are. More significant is the author's approval of a theory of earth origin that involves a process of growth by accretion of "dust particles, meteorites, and planetoids," a concept immediately reminding the geologist of certain phases of the Chamberlin-Moulton planetesimal hypothesis.

I spent a week with Professor von Weizsäcker in Switzerland during the summer of 1948, and consequently I can say that this book is absolutely characteristic of him. There is the same eager quest for truth and wisdom, the troubled concern for human welfare, the splendid humility of a fine spirit, the unwillingness to express ideas until they are fortified by abundant facts and cogent reasoning, that he displayed in our personal contacts on that occasion. One might wish that in his book he did not quite so often write "I cannot attempt that in this work"; but, on second thought, one realizes fully why he thus restrains his pen from rambling away from his central theme. It is a worthy theme and treated most expertly.

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Geology for Engineers. By JOSEPH M. TREFETHEN. New York: D. Van Nostrand Co., Inc., 1949. Pp. 620; tables 31; figs. 240. $5.75.

The title and the Introduction of this book show that the author fully understands the

purpose of a basic course in applied geology for civil engineering students—not engineering geology, but geology for engineers.

The book begins with a description of the rock-forming minerals. Instead of discussing fifty minerals or more, the author has reduced the number to nine, which the student can reasonably be expected to know. Although their physical and chemical properties are explained very carefully, the author has neglected to mention certain of their properties which are very important in engineering, such as the sudden expansion of quartz at 573° C. and the destruction of masonry by the decomposition of sulphide minerals. It seems almost superfluous to include the pyroxene and olivine groups in a book for engineers, as Trefethen has done. The classification and description of rocks is short and clear, and attention is paid to those properties pertinent to engineering problems.

After the study of rocks, the author takes up rock weathering and soils and includes a short introduction to soil mechanics. This chapter is written from the geological standpoint, without, however, bothering the student with many technical formulas. A chapter on geological structures is followed by a discussion of geological field work and geophysical exploration in engineering, which should enable the engineer to understand such work and to interpret the reports of experts. These chapters are excellently adapted to the needs of an engineer, but, like that on earth history, their placement may not be clear to the teacher or student.

The reader is surprised to find a chapter on earthquakes between that on subsurface water, which follows next, and that on surface water. The chapter on earth movements is, however, excellent; the author uses Sharp's classification of landslides and gives a good object lesson on the prevention and control of these important and malicious phenomena. The description of the exogenic forces of the earth continues with a complete explanation of stream morphology and stream control, followed by the chapter on dam sites and reservoirs, in which all details of the construction of dams and their abutments are considered very carefully. However, the responsibility involved in such large-scale construction work is so great that many additional illustrative examples should have been cited of the numerous failures of the past.

Most geology books discuss soil erosion only as a subchapter to mass wasting, but the author assigns this very important chapter its proper weight in his book. In addition to three tables, he presents two striking diagrams on the relation between intensity of rainfall and slope inclination, respectively, on soil erosion. He continues with a description of the effects of ice action and the influence of topography on erosion, including an excellent table on the sorting and occurrence of drift deposits.

The book closes with chapters on geological interpretation of topographic maps and aerial photographs, containing carefully selected portions of topographic quadrangle maps and good reproductions of airplane photographs. The position of this chapter is good; and it might have been preferable had those on field work, geophysical exploration, and geological maps been placed immediately before it.

Each chapter includes very useful references on the most important pertinent publications, and in addition there are three appendixes, which contain sources of geologic information, tables on the physical properties of various rock types, and thirty-two tables for the identification of common minerals.

Although the chapter arrangement of Trefethen's book is unusual and at times confusing, the adaptation of the subject matter to the needs of its intended readers is admirable. The value of the book would perhaps have been increased by additional illustrative examples in most chapters, but this and certain other shortcomings are only minor compared to the great advantages of the book. The author understands so fully the need for a textbook of applied geology for the civil engineering student and has been, in general, so successful in his endeavor to fill this need that this book is the only textbook in its field which the reviewer would recommend at present.

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Géologie des gites minéraux. By E. RAGUIN. 2d ed. Paris: Masson & Cie, 1949. Pp. 641; figs. 145. Fr. 1,650.

The high quality of this book is improved in the second edition by several additions and revision of the classification of the processes of ore genesis. A noteworthy feature of this book is the emphasis placed on the geology of the mineral deposits. On the other hand, the problems of mineral chemistry and many technical aspects

of ore deposits, familiar to advanced students, have been touched upon only briefly.

The general part of the book, chapters 1–4, contains a fairly detailed discussion of underground water and thermomineral springs. The ore-forming processes are discussed under the following headings: "Igneous Deposits," "Hydrothermal Deposits," "Deposits by Surficial Waters," and "Sedimentary Deposits."

Chapters 5–24 contain a systematic description of the occurrence of different minerals and ores, treated substance by substance. This arrangement facilitates the use of the work as a handbook. Each chapter deals with the use of a mineral or metal and its production up to 1945 (according to the *Minerals Yearbook* and reports of the Ministère de la Production Industrielle). The descriptions of important minerals are arranged according to type of occurrence and country.

The descriptive chapters are entitled: "Combustible Minerals," "Petroleum," "Calcium Phosphates," "Lacustrine Deposits (Salts)," "Substances Based on Lithophile Elements," "Magnesium," "Radioactive Substances and Rare Earths," "Tin, Tungsten, and Molybdenum," "Graphite, Titanium, and Vanadium," "Manganese," "Platinum, Chrome, Nickel, and Cobalt," "Iron," "Sulphur, Pyrite, Selenium, Tellurium, Arsenic, Antimony, and Bismuth," "Copper," "Zinc, Lead, and Cadmium," "Silver and Mercury," and "Gold." The absence of a general index is regrettable.

The descriptions of the deposits are excellently written and are illustrated by good sketches, maps, and profiles by the author. For American readers the detailed treatment of several less-known, but, from the geological point of view, important, European ores is of great interest. In general, the choice and the length of descriptions give a fairly good picture of the present importance of the principal mineral and ore deposits of the world. Minor shortcomings are the very brief description of the Canadian asbestos deposits compared with the detailed description of the Russian and African deposits, and also the scanty information about the titanium deposits of Quebec. But such defects can hardly be avoided in a book dealing with the whole world. In the second edition several new developments have been added, and certain descriptions have been revised.

The references given at the end of each chapter list the most important papers. Though mainly in French, many references in English and German are cited. The book can be recommended as a textbook for advanced students and should be very useful to anyone who wishes a good up-to-date general description of the mineral resources and production of the world.

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"Geology of the Pike River Coalfield, North Westland." By H. W. WELLMAN. (*New Zealand Jour. Sci. Technology*, vol. 30 [B].) Pp. 84–95. 1948.

This paper, with a somewhat unpromising title, gives an account of how the Paparoa Range, near the west coast of the South Island of New Zealand, "has been turned inside out," a process of introversion which the author proposes to call "eversion." Two periods of anticlinal upheaval are recognized, pre-Miocene and very late Tertiary, the latter making the initial landscape form of the range as it exists today. The belt thus upheaved was a geosyncline no more than 6 or 7 miles wide, in the axis of which some 10,000 feet of sediments had accumulated in late Cretaceous to Oligocene times. Thus the history of geosynclines in general has been repeated, but this example is a midget both in space and in time.

Stages of early Tertiary sedimentation, which are represented in eastern districts of the South Island by formations only a few feet thick, here swell to thousands of feet. Not all members of the thick lens postulated have survived in measurable remnants, but Wellman, by restoring formations destroyed by erosion, adds thousands more to the several thousand feet that are left. The evidence for this is circumstantial but plausible; the conclusion is based in part on the high rank of bituminous coals in the Pike River coal field, an outlier perched near the crest of the range at an altitude of 3,000 feet, which is taken as an indication of the former presence of a thick cover.

In a diagram showing four stages of development, the present anticlinal structure of the range is compared with two (early) stages of geosynclinal sinking and one of mid-Tertiary arching followed by peneplanation. The final, more vigorous, upheaval was contemporaneous with development of strong tectonic relief throughout most of New Zealand. Miocene sedimentation is assumed to have buried the truncated mid-Tertiary anticline, but without a return to geosynclinal conditions.

The evidence of eversion has been preserved by a "fortunate geological accident," the formation during the later and more intense orogenic spasm of a fault angle along the crest of the anticline, in which an outlier of the thick sediments deposited in the axis of the geosyncline is preserved, being protected to some extent from erosion by its juxtaposition along the fault with a portion of the resistant undermass forming the anticlinal core, the older rock mass being, to some extent, thrust over the softer coal measures and sandstone.

For the latter part of the Tertiary, the interpretation offered by Wellman fits in to some extent with Macpherson's (1946) generalizations of New Zealand structure; for earlier times their views are divergent, but the geology of the Paparoa Range is probably exceptional. Macpherson has announced a persistence of "highs" and "lows" throughout late Cretaceous and Tertiary time, the former being narrow synclinal belts comparable in a small way to the idiogeosynclines of Umbgrove, in which thick, open-water sedimentary strata are unbroken by unconformities, the latter being intermediate belts in which shallow-water sedimentation was frequently interrupted by emergence. Some of the highs are thought to have become embryos of the tectonic ranges, now to some extent fault-bounded, which were upheaved much more vigorously at or near the end of Tertiary time. Evidence for such embryos and persistent lows has been found, especially in the eastern districts of the North Island, but evidence is present probably in other parts of the region, notably in eastern Otago, where Benson has remarked that the "tectonic character . . . seems remarkably persistent."

In Macpherson's example from Poverty Bay (1946, p. 17), intermittent uparching of a high is recorded throughout the Upper Cretaceous and Tertiary, with development of ten or eleven slight to strong discordances. A crescendo of diastrophism is noted, however. There is an "initial prolonged period of subsidence," continuing until the end of the Oligocene, during which "only seemingly mild orogenic impulses" recorded themselves (p. 13). Probably these would appear negligible in the many places characterized by a very long and slow accumulation of "fine, light coloured sediments," as Macpherson describes them, and by "absence of coarse clastics" (p. 13). Sedimentation from Upper Cretaceous to Oligocene time was uninterrupted by emergence or by changes which could not be accounted for by fluctuation of ocean level. After the Oligocene, on the other hand, Macpherson notes, "recurrent orogenies with noteworthy change in sedimentation became marked." It is to this latter period that the orogenies recorded by Wellman are referred.

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MACPHERSON, E. O. (1946) An outline of late Cretaceous and Tertiary diastrophism in New Zealand: New Zealand Geol. Mem., no. 6, 32 pp., map.

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"La Glaciazione quaternaria dell'Appennino settentrionale." By UGO LOSACCO. (*Riv. geog. italiana*, annata 56, fasc. 2, pp. 90–152; fasc. 3, pp. 196–272.) 1949.

After the Miocene the northern Apennines were subjected to a long period of erosion which produced a mature land surface, remnants of which are visible chiefly in the central part of the chain. On this surface, glaciation occurred during the Pleistocene. The glaciers were all of small dimensions; only about ten reached a length of 3 miles, and only one reached a length of 5 miles. *Vedrettas* ("glacierettes") were particularly abundant, but there were also many valley and alb glaciers. The total number of glacial cirques, including minor ones, is about one hundred and thirty. Most cirques do not have typical form, mainly because of the feeble development and short duration of the Appenninic glaciation and the weak rocks of the region. Most of the cirque floors are 4,600–4,900 feet in elevation.

The glacial drift is represented by morainic deposits and erratic boulders. Ground moraines are particularly well shown in the valleys, some of them reaching a thickness of about 300 feet. Moraines also occur on the albs, and transverse morainic ridges are typically present on the thresholds of cirques and on valley steps.

The altitude of the regional snow line has been calculated according to a modification of the method of Kurowski, i.e., using the arithmetic means between the maximum altitude of the walls of the cirques (or the mean of the altitudes of their surrounding peaks) and the minimum altitude at which the related drifts are found. The snow line thus calculated rises gradually toward the southeast; in the western part of the

chain it is about 4,000 feet in elevation, while in the eastern part it is about 4,700 feet.

All the evidence indicates that only one glaciation, the Würm, took place in the northern Apennines, which supports the observations of De Lorenzo and Dainelli in the southern Apennines and Jaranoff in the Balkans. The explanation commonly accepted—and subscribed to by the author—is that the uplift of the entire Apenninic chain, as well as that of the Balkans, continued throughout the glacial period and that it was only during the Würm stage that these regions reached an altitude that allowed glaciation.

The retreat of the glaciers after the climax of this single glaciation was not continuous but was interrupted by three recessional phases, during which transverse morainic ridges were formed. The first recessional phase raised the snow line about 900 feet above its level at the climax of the glaciation; the second recessional phase raised it another 200 feet; and the third phase, 230 feet more. The last recessional phase was more important than the previous two and is believed possibly to correspond with the Bühl phase of Alpine glaciation. In postglacial time the entire chain was subjected to further uplift, and the valley floors and their related moraines were deeply incised and terraced.

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Regular Polytopes. By H. S. M. COXETER. Edinburgh: T. and A. Constable, Ltd.; New York: Pitman Pub. Corp., 1947. Pp. xix+321; figs. 85; pls. 8; tables 8. $10.00.

That a review of this text on a purely geometric subject should find its way into the *Journal of Geology* might at first seem strange. Perhaps the title itself will attract the mineralogist and morphological crystallographer, as a few common crystal forms (tetrahedron, cube, and octahedron) can be classed as regular polyhedra. However, it is the chapters on rotation groups and on tassellations and honeycombs that should command the greatest attention of the structural crystallographers.

Professor Coxeter is not presenting a monograph on any original work but, rather, is giving us a textbook. The first two chapters are concerned mainly with the properties of regular and quasi-regular solids and the construction of graphs and maps. The third chapter is entitled "Rotation Groups" and presents a development of transformations and symmetry operations paralleled by a brief but adequate development of elementary group theory. The remaining portion of the chapter, as well as subsequent chapters on tessellations, honeycombs, and the kaleidoscope, show the applications of group theory to symmetry operations; and the limitations imposed upon discrete groups of displacements in a plane and in space are discussed. The presentation of this material, as well as the order in which it is discussed, is considerably different from the more rigorous derivations of the crystal classes and space groups more familiar to the average mineralogist. This in itself is refreshing and could give one a broader insight into the geometry of lattices. The last eight chapters of the book are devoted to the development and properties of figures in n-dimensional space.

Since the text is not designed especially for the crystallographer, it would be unfair to criticize the fact that a derivation of the crystal classes or space groups is not presented beyond a development of group theory and a few applications to symmetry operations. However, much of the writing lacks clarity. It is an admittedly difficult task to describe geometric forms and actions in words, but a few additional diagrams would have made more lucid such portions of the text as the development of the glide reflection and that of the rotatory reflection. The lack of rigor in some of the proofs might leave considerable uncertainty in a student's mind. Wigner's rather sketchy proof of the theorem that only 2-fold, 3-fold, 4-fold, and 6-fold rotations can exist in a plane that has more than one center of rotation is given, rather than a more exacting one like that presented by Bravais in 1850.

At the conclusion of each chapter there is a brief section containing historical remarks, which helps considerably to increase the appreciation of the subject matter.

As far as the mineralogist is concerned, the appearance of this text serves to remind us of the crying need for a textbook, in English, on mathematical crystallography.

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Die jungen Eruptivgesteine des mediterranen Orogens, Vol. 1: *Einleitung—Die Ophiolite-Allgemeines über das Verhalten basischer*

Magmen—Berechnungsmethoden. By CONRAD BURRI and PAUL NIGGLI. Zurich: Vulkaninstitut Immanuel Friedlaender, 1945. Pp. 654; figs. 201; pls. 6. Vol. 2: *Der Chemismus der postophiolitischen Eruptivgesteine.* By CONRAD BURRI and PAUL NIGGLI. Zurich: Vulkaninstitut Immanuel Friedlaender, 1949. Pp. 206; figs. 4; pls. 3.

This work comprises two remarkable and impressive volumes hardly comparable to anything else in petrographic literature, compelling the admiration and respect of every petrologist able to read German. The work, although mainly petrochemical, has a wider scope, being a treatise on the young magmatic rocks of the Mediterranean, on their distribution and chemistry, and on the relation between geological milieu and rock character. In addition, in order to throw light on the broader and more general aspects of petrogeny, a great many other rock provinces are analyzed and thoroughly discussed for comparison. For instance, the famous Skaergaard intrusion (Greenland), so ably described by Wager and Deer, has been given no less than 48 pages of text, figures, and tables. Other well-known provinces have likewise received special consideration: Bushveld and Karroo dolerites and their differentiates in South Africa, the Hawaiian lavas, the San Franciscan volcanic field (Arizona), the north British Tertiary province, the central Victoria volcanite area (Australia), and many others. Taken together, these discussions cover 380 pages, or more than half the first volume.

The petrochemistry is presented in the symbolic language of Niggli. A full account is given of the various methods of petrographic calculations used by the Niggli school. Thousands of rock analyses are recalculated accordingly and arranged in all kinds of ingenious diagrams—but nowhere can one find the ordinary weight percentages familiar to most American petrologists. Everything is given in terms of the numerous and various Niggli symbols.

The *ophiolites* from the Alps, Apennines, Pyrenees, and Balkans, products of the initial magmatism of the geosyncline, are shown to exhibit great similarities in chemistry and trend of differentiation. They correspond to basic magmas, having differentiated in a characteristic way, and are in all regions associated with peridotites. In many particulars they differ chemically from the usual basic eruptive rocks, but, generally speaking, they have many features in common. The subsequent metamorphism took place without much material transfer and has, in fact, conserved rather than destroyed the original chemical composition.

The ophiolitic magmas comprise differentiates of "pacific" affinity, as well as such of olivine basaltic-alkali basaltic-mugearitic affinities. But members of the truly "atlantic" rock suites are missing.

It is concluded that the ophiolitic magmas were derived from the sima which, possibly through assimilation of sialic material, became slightly silicified.

The *postophiolitic* magmatic rocks are the products of (1*a*) synorogenic plutonism and (1*b*) subsequent volcanism, both derived from sialic material, and of (2) final volcanism of simatic relations. From these rocks in the Mediterranean orogene, from Gibraltar to the Armenian plateau, 2,138 analyses have been collected and statistically treated. The geological locales are partly the main geosyncline, partly the marginal districts and the "Zwischen-Gebirge," partly fault zones of the forelands. Consequently, rock suites are encountered belonging to the calcalkali (pacific) series, as well as to the more alkaline series (atlantic and mediterranean).

Useful for recalculating chemical rock analyses are the appended tables of the molecular proportions corresponding to different values of weight percentages of the usual rock-making oxides.

A third and final volume is announced, treating the individual provinces and the relations between mineral and chemical composition.

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Geology Applied to Selenology, Vol. 4: *The Shrunken Moon.* By J. E. SPURR. Lancaster, Pa: Business Press, 1949. Pp. 207; figs. 36. $4.00.

The Shrunken Moon is the fourth volume of a treatise by J. E. Spurr on the origin of the moon's surface features. The three previous volumes are entitled *The Imbrian Plain Region of the Moon, The Features on the Moon,* and *Lunar Catastrophic History.* In the present volume Spurr again ignores a possible meteoric-impact origin for lunar surface features and further develops his thesis that they are the result of special types of volcanism and of other internal forces.

As the title implies, this book is concerned with developing the particular thesis that the moon has decreased enormously in size and ellipticity. According to Spurr, a decrease in equatorial diameter from about 3,000–4,000 miles to a present diameter of about 2,000 miles has been accompanied by volcanism, by the expulsion of great quantities of gases, and by periodic crustal shortening, which caused lunar orogenies. Most of the crustal shortening occurred in equatorial regions because the two major axes of the original lunar ellipsoid were in the equatorial plane.

Analogous to geological practice, the writer has subdivided the history of lunar events into three eras—the Proteroselene, the Mesoselene, and the Teleoselene. Each of these is further subdivided into an Early, Middle and Late period. Capture of the moon by the earth and cessation of independent rotation is ascribed to the Middle Proteroselene; the major revolution, during which Mare Imbrium was formed, is ascribed to the Middle Mesoselene.

In addition to sixteen chapters which form the body of the text, the volume has sections entitled "Introduction," "Summary," "Lunar Time Divisions," "Correlation of Craters," and "Addenda." The initial chapters discuss the north and south polar regions of the moon, and much is made of the fact that, like the earth, the lunar south pole is topographically positive and the lunar north pole is topographically negative. Several succeeding chapters deal with structural interpretations of lunar features, such as fault zones, lattice patterns, a feature called the "Central-meridianal Horst," and hexagonal craters. In regard to the latter, Spurr claims that hexagonal patterns can be caused by either compression or tension, and he invokes both to explain hexagonal lunar craters. Subsequent chapters are devoted in large part to interpretations which attribute lunar structures to great crustal compression.

Spurr has scrutinized the moon's surface with great care and has described the individual features and geomorphic pattern in more detail than has been done before. This is the first time that lunar features have been studied carefully by one trained and experienced in modern structural and igneous geology. Further, he appears to be the first to add, in any great detail, the time dimension to selenology. Strangely enough, this has been ignored almost completely by most selenographers. In the course of the investigation he has uncovered many new and significant details and correlations. One needs to read the earlier volumes and have a good lunar map available, in order to get the most out of this book. A set of moon photos, such as those available from the Mount Wilson Observatory, is a distinct aid to a study of the treatise.

The volume has several shortcomings. It is not at all well organized, the terminology is obscure, and it is difficult to read. The illustrations consist entirely of sketches, which are necessarily subjective. The use of photographs, tables, graphs, etc., would have helped the understanding and improved the readability of the text. In developing his arguments, the author does not refer to the work of others. Consequently, his speculations are unsupported by the existing body of scientific fact. His arguments are purely descriptive, empirical, and qualitative and, accordingly, not entirely convincing. He falls into some of the same pitfalls which snared the early selenographers who ignored the scale effect and explained lunar craters in terms of "kitchen experiments." For example, Spurr genetically compares the craters to bubble-holes in evaporating paste. Although the case for the meteoritic-impact theory has been strongly developed in recent literature, the writer nowhere attempts to evaluate this theory but rather simply states "the theory of the origin of moon craters by impact of meteoric missiles . . . is an inverted pyramid, so small is the basis on which the structure rests."

Although Spurr has made an important contribution to the science of the moon, his speculations regarding the origin of its surface features are not convincing.

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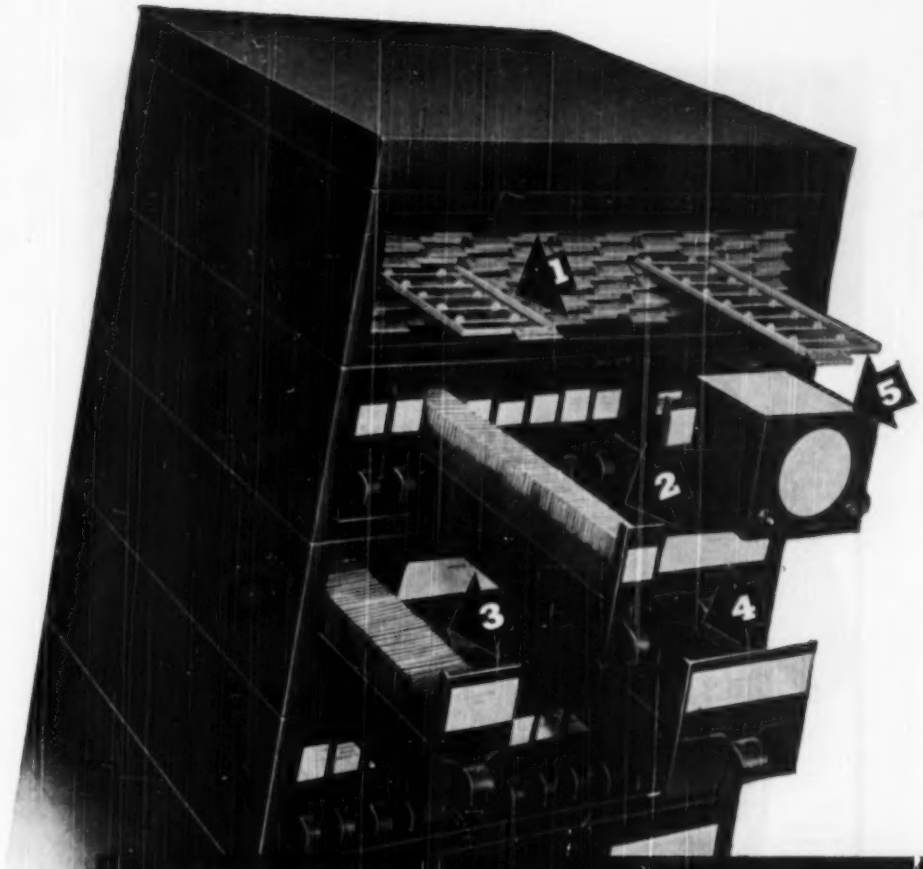

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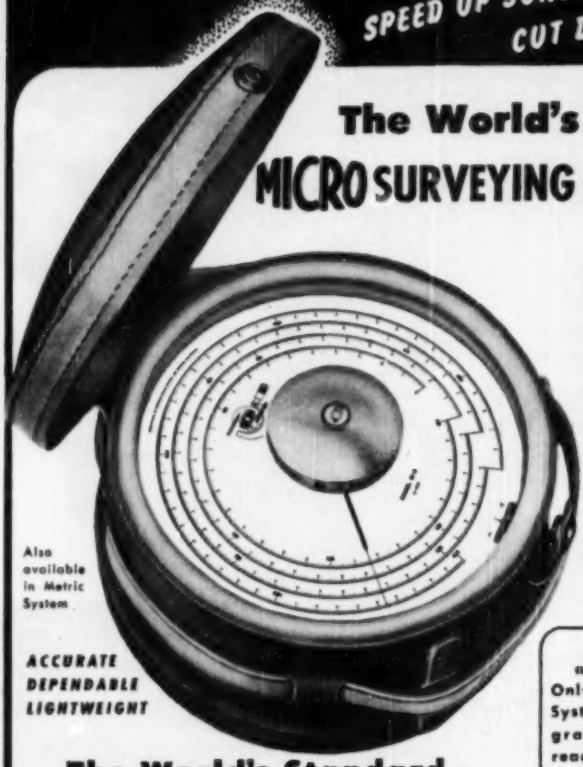

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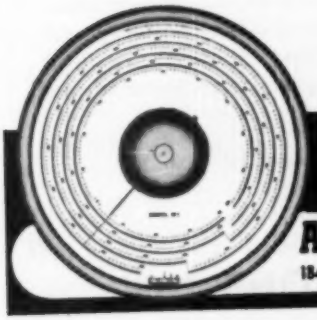

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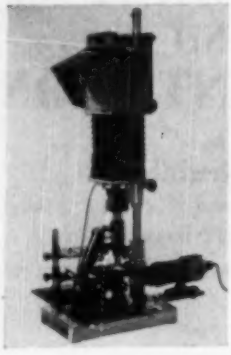

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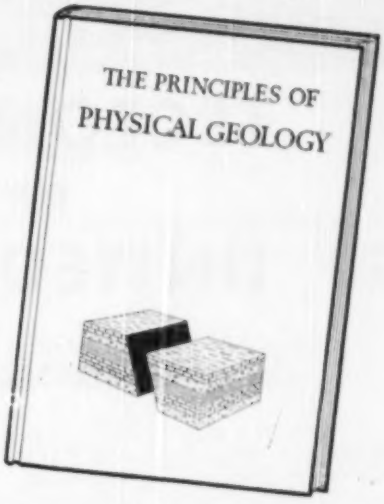

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